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Benthic Community Structure in Relation to an Instantaneous Discharge of Waste Water from a Tin Mine

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Southwest Cornwall, UK, has a long history of metal mining which has resulted in the establishment, over historical time, of a marked gradient in heavy metal concentrations in the sediments of creeks in the Fal Estuary system. In 1991 Wheal Jane, the last tin mine in the Carnon Valley, closed and the mine workings and Tailings Dam filled with acidic metalliferous water. A plug in the Nangiles adit gave way in January 1992, causing a massive discharge of this water, via the Carnon river, into Restronguet Creek and Carrick Roads. At that time the event was widely reported in national news media as a major catastrophe. Sediment samples for analyses of sediment metal concentrations and associated infaunal communities were collected in November 1991, in anticipation of this event, and again in March, 2 months after the overflow. Analyses of the heavy metals data showed that there was no significant difference in sediment concentrations between these dates. Small changes were found in the meio- and macrobenthic communities but these could be attributed to natural fluctuations in populations over the intervening winter period. We conclude that the overflow had no significant effect on the benthic infauna in the estuary.

Mining for metals in Cornwall, UK has a long history, probably stretching back to the Bronze Age for the recovery of alluvial tin. In the middle of the nineteenth century in excess of 1000 mines, of which more than 50 were in the Carnon Valley, produced up to 50% of the world's supply of copper, tin and arsenic, but output declined sharply during the twentieth century. The last tin mine in the Carnon Valley, Wheal Jane, closed in March 1991 and pumps that had been de-watering the mine were removed. As a result water in the mine, which was acidic and contained significant levels of heavy metals (including Cd, Zn, Ni, As, Cu, and Fe), began to rise. The water reached the surface on 17 November 1991 and began discharging to the Carnon river. A contingency plan which involved treating the water with lime and pumping it into a settlement area known as the Tailings Dam was put into effect (National Rivers Authority News Release, 30 January 1992). Although this strategy was successful for a few weeks, water continued to back up in the mine and began to emerge untreated from various exit routes. On 4 January 1992 pumping to the Tailings Dam stopped for technical reasons. While alternative methods of treatment were being investigated, an underground collapse of a plug in the Nangiles adit led to untreated water which had backed up in the mine breaking out on 13 January 1992. Approximately 45 million litres of acidic (pH 3.1) metal laden (Cd concentration >600 μl l^{-1}) water discharged via the Carnon river into Restronguet Creek (Fig. 1), where they met with neutral sea water. Some metals in the discharge, in particular hydroxides of Fe, came out of solution to form an opaque ochre-coloured slick. At the height of the discharge, discoloured water spread with the tide from Restronguet Creek as far as Falmouth. The environmental health implications caused much concern to residents in the area, and the incident was widely reported in national news media. Pumping to, and treatment of waters in, the Tailings Dam resumed on 21 January 1992, and metal concentrations in the river water entering Restronguet Creek quickly returned to pre-November levels (Fig. 2).

Over the centuries inputs from mines, adits, tailings and spoil heaps had produced a marked gradient of sediment metal concentrations in creeks leading into Carrick Roads. In the 1970s sediments, in otherwise similar creeks in different parts of the Fal Estuary system, had levels of heavy metals (including Cu, Zn, As, Cd, Fe) which differed by orders of magnitude (Bryan & Gibbs, 1983) and sediment Cu concentrations in Restronguet Creek are the highest in the UK (Bryan & Langston, 1992). Thus, with a gradient in heavy metal pollution over historical time and the possibility of an instantaneous input from the Wheal Jane mine, the Fal Estuary system presented an ideal site for a natural experiment on the long- and short-term effects of heavy metal pollution on benthic communities. Somerfield *et al.* (1994) have examined

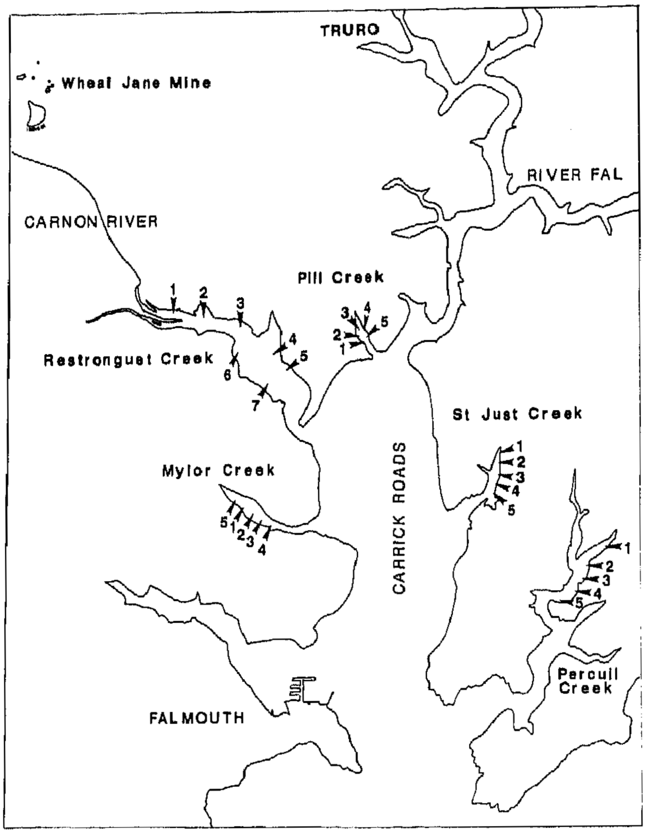

Fig. 1 Map of the Fal Estuary system, Cornwall, UK showing the location of the Wheal Jane mine and sampling sites.

the effects of the long-term gradient on meiofaunal community structure.

Materials and Methods

Based on sediment copper data in Bryan & Gibbs (1983), five creeks debouching into Carrick Roads were chosen (Restronguet, Mylor, Pill, St Just in Roseland, and Percuil) to cover the expected range of heavy metal concentrations. On 7 and 8 November 1991 (before the discharge from the Wheal Jane mine) five sites (seven in Restronguet) along each creek were selected as representative of that creek and as far as possible with similar environmental characteristics, being at the same distance from the central stream and confined to banks of mud.

At each location (Fig. 1) a single core was taken for meiofauna (50 ml syringe to a depth of 5 cm) and macrofauna (20 cm diameter core to a depth of 20 cm). Surficial sediment was collected for analyses of metal concentrations, % silt/clay and % organics, and frozen at −20°C pending analysis. This survey was repeated on 4 and 5 March 1992.

After fixation in 4% buffered formalin, samples for meiofauna (copepods and nematodes) were washed on a 63 μm sieve to remove formalin and most of the finer sediment fraction. The meiofauna were then extracted

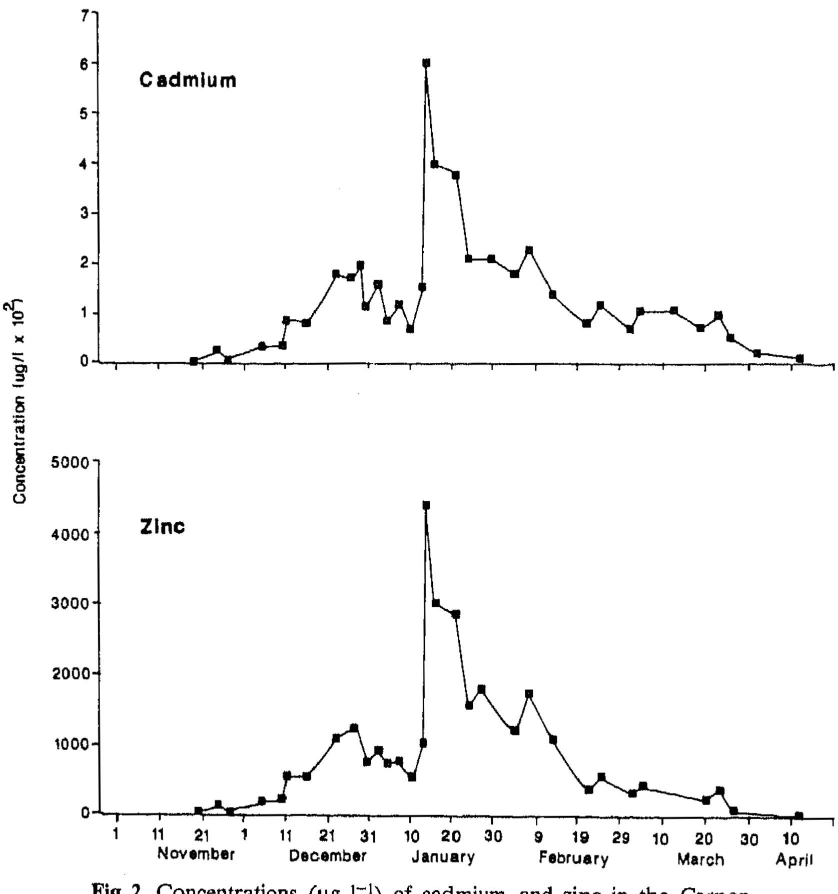

Fig. 2 Concentrations (μg l^{-1}) of cadmium and zinc in the Carnon river at Devoran Bridge, November 1991 to April 1992 (*source:* National Rivers Authority News Release, 24 April 1992).

using elutriation in fresh water and decantation through a 63 μm sieve followed by a flotation extraction using a colloidal silica solution (Ludox™ from DuPont) with a specific gravity of 1.15. The copepods were picked out of each sample under a binocular microscope and identified to species in hanging-drop mounts, or by dissection. The remaining meiofauna were slowly evaporated to anhydrous glycerol, evenly spread on microscope slides and the coverslips ringed with Bioseal. Nematodes were counted and the first 200 specimens encountered in each sample identified to species, allowing the total numbers of each species in each sample to be estimated. Macrofaunal samples were sieved on a 500 μm mesh, fixed in 4% buffered formalin, stained with 5% Rose bengal, the fauna sorted by hand and identified to species.

Sediment samples were dried at 80°C. For the determination of metal concentrations dried samples were digested in conc. HNO_3 and, after evaporation, the residues were dissolved in 1 M HCl. Metal concentrations were determined by flame atomic absorption using a Varian Spectr AA20 atomic absorption spectrometer with autosampler. Background correction was used for elements other than Cu, Zn and Fe. An air/acetylene flame was used for all metals except Cr, for which nitrous oxide/acetylene flame was used. The % organic matter in samples was estimated by the loss of weight on ignition at 600°C after removal of carbonates by treatment with 8% HSO_3. The % silt/clay in sediment samples was determined by wet sieving using a 63 μm sieve to separate the coarse and fine fractions which were then dried at 95°C and weighed.

Data Analyses

Analyses of environmental variables

Ordination of environmental data used a correlation based Principal Components Analysis (PCA). The significance of differences between creeks and dates was tested by applying the randomization/permutation test ANOSIM (Clarke, 1993) to the Euclidean distance matrix underlying the ordination (Clarke & Green, 1988), and by two-way crossed ANOVA. Log transformations were used throughout.

Analyses of community structure

The significance of differences in total abundance and diversity (Shannon-Wiener diversity function calculated using natural logarithms) of nematodes, copepods and macrofauna was tested using two-way crossed ANOVA. Non-parametric multivariate techniques were used which are discussed in a recent review by Clarke (1993) and are included in PRIMER (Plymouth Routines in Multivariate Ecological Research), a suite of computer programs developed at the Plymouth Marine Laboratory. Ranked lower triangular similarity matrices were constructed using a range of data transformations, the Bray-Curtis similarity measure and group-average sorting. Transformations were used to reduce contributions to similarity by abundant species, and therefore to increase the importance of the less abundant species in the analyses. Nematodes and macrofauna vary in abundance between single individuals and thousands of specimens within samples, so a fourth root transformation was applied. Copepods vary between single specimens and hundreds of specimens, so a square root transformation was used. Ordination was by non-metric multidimensional scaling (MDS) (Kruskal & Wish, 1978; Clarke & Green, 1988). Formal significance tests for differences between creeks and dates were performed using the ANOSIM permutation test (Clarke & Green, 1988). The species contributing to the average dissimilarity between November and March for each creek were determined using the similarities percentages procedure SIMPER (Clarke, 1993).

Results

The ordination techniques used map samples into two dimensions in such a way that the distances between samples reflect the degree of similarity between them, and therefore it is the position of samples relative to each other that is important, and axes are not shown. The PCA ordination (Fig. 3) of environmental data (Table 1) shows that all the creeks were different. Stations in Restronguet Creek are widely separated from the rest. ANOSIM confirms that the differences between creeks were all significant ($p < 1\%$). Differences between dates (Table 2) were not significant ($p > 5\%$) other than a marginally significant ($p = 1.6\%$) difference in Pill Creek. Taking only sediment metal concentrations into consideration even this difference was reduced in significance ($p = 4.8\%$). Two-way crossed ANOVA showed no significant interaction between time and creek effects. Thus the short-lived pulse of elevated metal levels in the water flowing into Restronguet Creek did not lead to significant changes in metal levels in the sediments of Restronguet Creek. Indeed, the November and March samples from the head of Restronguet Creek (Station R1), closest to the source of input, cluster closely together (Fig. 3).

Although some differences in total abundances were significant they did not occur in a pattern consistent with a pollution impact in Restronguet Creek. Nematode abundance decreased significantly in Mylor and St Just Creeks, copepods in all creeks except Pill, and macrofaunal abundance in Pill Creek. Diversity (H′) of nematodes and macrofauna did not change significantly, whereas a decrease in copepod diversity in all creeks was significant ($p < 0.1\%$).

The MDS ordinations of biotic data (Figs 4–6) show similar patterns, with Restronguet Creek separated from the rest. In the ordination of nematode abundances creeks other than Restronguet are also separated from each other in the order Mylor, Pill, St Just and Percuil, a pattern consistent with decreasing metal concentrations. Only the communities in Mylor and Pill Creeks differed significantly between November and March ($p < 1\%$) (Table 3). SIMPER showed that these dissimilarities were the result of changes in the relative abundances of common species.

In the ordinations of copepod and macrofauna data, samples from Mylor, Pill, St Just and Percuil Creek are

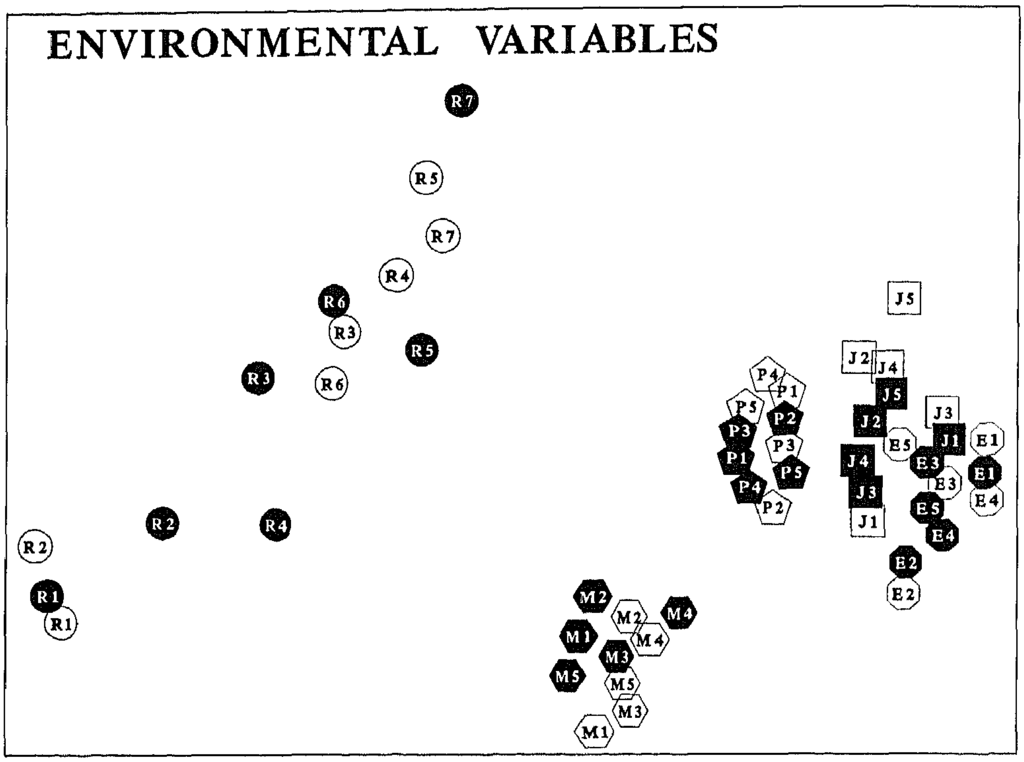

Fig. 3 Ordination by correlation based PCA of log-transformed environmental variables from sites in Restronguet (R1–7, circles), Mylor (M1–5, hexagons), Pill (P1–5, pentagons), St Just (J1–5, squares) and Percuil (E1–5, octagons). Creeks from surveys in November 1991 (white symbols) and March 1992 (black symbols).

TABLE 1

Means and standard deviations of % silt/clay (1), % organic matter (2) and heavy metal concentrations ($\mu g\ g^{-1}$ dry weight) in sediments from five creeks in the Fal Estuary system, November 1991 and March 1992.

	1	2	Ag	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Restronguet												
November												
Mean	69	6.3	3.63	2.75	21.9	38.7	2532	55 845	539	30	209	3814
S.D.	13	1.4	0.91	1.03	4.1	4.9	575	8685	44	4.7	42	1295
March												
Mean	77	5.23	3.06	2.65	19.9	39.9	2291	69 738	571	29.7	188	5934
S.D.	15	1.3	0.73	0.8	2.5	4.3	532	15 548	53	4.7	38	2254
Mylor												
November												
Mean	95	8.5	2.33	1.47	12.9	59.7	1272	40 768	395	32.8	188	1431
S.D.	3	0.3	0.11	0.17	0.5	4.9	62	1426	15	1	7	59
March												
Mean	96	8.3	2.47	1.49	12.4	57.1	1286	45 812	418	31.9	177	2132
S.D.	3	1.2	0.18	0.17	0.5	3	132	3321	25	1.3	14	376
Pill												
November												
Mean	90	9.2	1.43	1.35	11.3	43.5	697	33 603	282	26.9	142	1006
S.D.	4	0.4	0.06	0.34	0.2	5.1	19	1074	13	0.9	8	69
March												
Mean	94	7.8	1.31	0.99	11	46.4	735	38 796	323	26.3	131	1584
S.D.	3	0.4	0.7	0.1	0.3	4.3	6.4	1638	13	0.4	3	162
St Just												
November												
Mean	81	12.8	0.62	0.85	9.51	44	332	29 703	249	26.6	93.9	624
S.D.	7	4.4	0.08	0.07	0.54	4.9	33	2812	10	1.3	8.8	33
March												
Mean	93	12.5	0.7	1.07	9.79	44.8	338	32 001	250	26.3	94.7	700
S.D.	3	1.9	0.07	0.22	0.28	4.8	22	1261	6	0.7	3.5	32
Percuil												
November												
Mean	92	8.7	0.32	0.32	7.87	49.6	165	31 647	221	28.9	72.8	302
S.D.	5	1.1	0.07	0.09	0.47	4	34	7863	39	0.9	4.5	62
March												
Mean	95	8.7	0.35	0.22	7.83	48.5	170	32 999	237	29.2	72.3	355
S.D.	3	2	0.06	0.04	0.41	5.5	9	1131	13	1.2	4	13

TABLE 2

The % significance of differences between creeks in November and March. Pairwise comparisons from one-way ANOSIM of transformed data. 1=All environmental variables, log transformation. 2=Sediment metal concentrations, log transformation. 3=Nematode abundances, fourth-root transformation. 4=Copepod abundances, square-root transformation. 5=Macrofaunal abundances, fourth-root transformation.

Creek	1	2	3	4	5
Restronguet	21.9	18.4	53.1	0.8	31.9
Mylor	11.9	13.5	0.8	0.8	0.8
Pill	1.6	4.8	0.8	0.8	0.8
St Just	5.6	84.1	14.3	1.6	0.8
Percuil	70.6	78.6	38.1	52.4	0.8

not ordered in a pattern that is consistent with decreasing metal concentrations, suggesting that other factors are influencing the community structure of copepods and macrofauna in these creeks. The copepod communities in Restronguet, Mylor, Pill and (marginally) St Just Creeks differed significantly between November and March (Table 2). SIMPER showed that dissimilarities of copepod communities between dates result from decreases in abundance of a broad range of species over the intervening period, with the exception of two species which increased in numbers in Pill Creek. Although the difference in copepod community structure in Percuil Creek was not significant, numbers

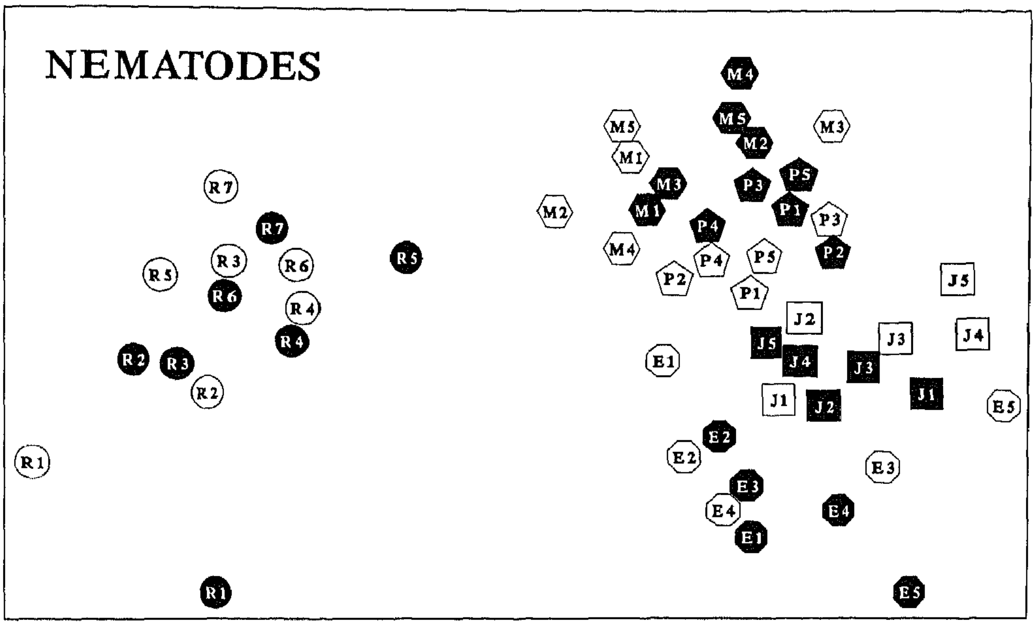

Fig. 4 Ordination by MDS of $\sqrt{\sqrt{}}$ transformed nematode abundance data (stress=0.16). Symbols as in Fig. 3.

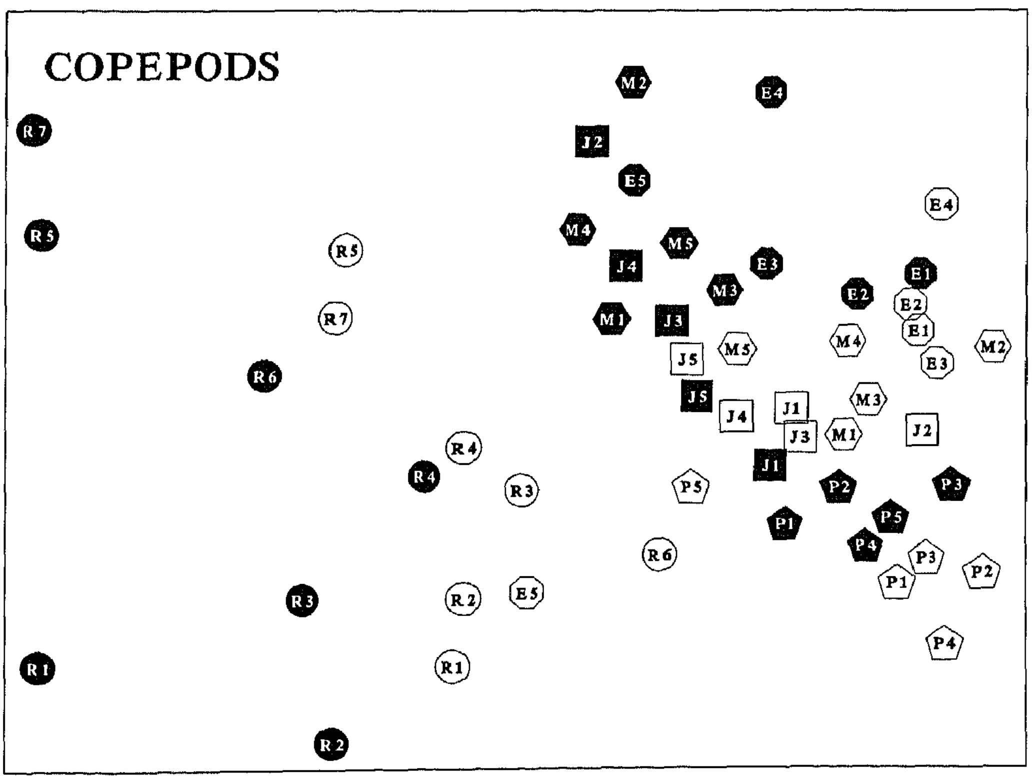

Fig. 5 Ordination by MDS of $\sqrt{}$ transformed copepod abundance data (stress=0.15). Symbols as in Fig. 3.

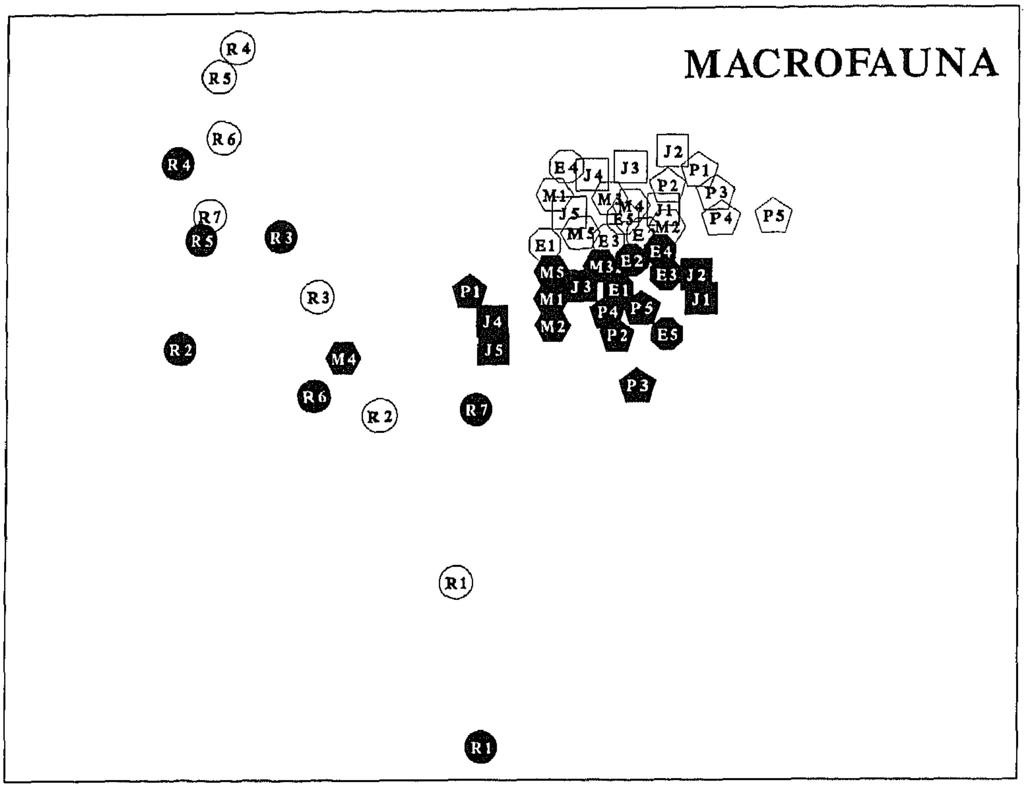

Fig. 6 Ordination by MDS of $\sqrt{\sqrt{}}$ transformed macrofaunal abundance data (stress=0.13). Symbols as in Fig. 3.

decreased there as well, and it seems likely that differences between creeks were a result of seasonal factors.

The macrofaunal community in Restronguet Creek did not alter significantly between November and March, whereas differences between dates were significant in all the other creeks ($p=0.8\%$) (Table 2). The species contributing to these dissimilarities were all small annelids which are known to decrease in numbers during the winter (Kendall, 1979).

Discussion

Despite the high concentrations of metals in the Carnon river for a short period in January 1991 no major change was detected in sediment metal concentrations in Restronguet Creek. There are many factors which could account for this. The normal pH range of estuarine water is 7–8.5. When river water mixes with estuarine water some of the trace metals dissolved in the river water are precipitated. If, however, the pH of the estuary is low then metals remain in solution. Evidence from the National Rivers Authority (NRA News Release, 28 February 1992) suggests that acidic fresh water (pH 4.65–5.75) tended to remain on the surface of the creek, and that the majority of the mixing between waters in the plume and seawater took place in Carrick Roads. Previous studies in Restronguet Creek (Bryan & Hummerstone, 1973) also demonstrated that acid water from the Carnon river flows over the salt water in the creek. Thus much of the metal dissolved in the discharge water was not precipitated within Restronguet Creek. Furthermore different metals behave in different fashions. Fe is readily precipitated, and was the source of the red coloration of the water and tidal flats in Restronguet Creek, Cu and Pb are adsorbed or coprecipitated by the oxides of Fe. Other metals such as Cd, Zn and Mn tend to remain in solution. The principal metals in the discharge from the Wheal Jane mine were Zn, Cd and Fe. Although other metals were present in the discharge their primary source of input into the Carnon river is via the County adit, which was unaffected by the events at Wheal Jane. Furthermore, although dissolved metal concentrations in the discharge were extremely high for a short period, the actual amount of metal released was small in comparison to the total amount of metal entering Restronguet Creek over historical time.

The question of bioavailability, assimilation and toxicity of heavy metals is enormously complicated and sediment concentrations are a poor guide to the potential toxicity of individual metals to benthic species (Bryan & Langston, 1992). Modifying factors include mobilization of metals to interstital water, their chemical speciation, transformations such as methylation of As and Pb, preferential binding of metals to sediment components such as organic matter and oxides of Fe, and competition between chemically similar metals such as Cu and Ag, Zn and Cd, for uptake sites in organisms. These processes are further influenced by physical factors such as salinity, oxygen concentration, pH and the stability of the sediment (Bryan & Langstone, 1992). Bacterial exopolymer secretions (Decho, 1990), mucus (Howell, 1982) and trophic relationships of species can further influence uptake of metals by benthic organisms. The major metals in the discharge were Zn and Cd, neither of which is considered to be particularly toxic to marine organisms (Bryan & Langstone, 1992). As neither was bound to sediments in appreciable additional quantities it must be assumed that any effects on the biota must have been limited to toxic effects of high concentrations of dissolved metals in the water column, to which organisms would only have been exposed for short periods during the tidal cycle, if at all.

Although significant, if small, differences were found in communities of benthic organisms between November and March none of these can be related unequivocally to the discharge from the Wheal Jane mine, and it is probable that differences were an effect of naturally occurring seasonal changes in abundance.

The use of meiofauna in marine pollution studies has evoked considerable interest in recent years (Heip *et al.*, 1988; Coull & Chandler, 1992) as they have several potential advantages over macrofauna (Warwick, 1993). These include the fact that meiofauna generally have shorter generation times (months rather than years) and reproduce continuously and therefore might be expected to respond to pollution events more quickly and to show less seasonal variability. Meiobenthic communities are, however, diverse and contain members of many phyla, with differing life-history strategies and physiologies. The majority of studies on the effects of pollutants on meiofaunal communities have concentrated on 'hard' taxa, that is those which do not need specialized methods of fixation and preservation. The dominant hard taxa in marine sediments are nematodes and harpacticoid copepods. Whereas these generalities do apply to the majority of nematodes this is not the case for many copepods.

Several harpacticoids have been shown to undergo marked seasonal cycles in abundance (Hicks & Coull, 1983). Although some nematode species do have abundance peaks at certain times of the year (Heip *et al.*, 1985) nematode communities comprise relatively high numbers of species and persist in numbers even in situations where macrofauna are excluded (Warwick & Clarke, 1993), and therefore the effects of changes in the abundance of single species do not have such a severe influence on overall community structure. Comparing the distribution of samples from November and from March in the biotic ordinations it would seem that differences between creeks are maintained in ordinations of meiofaunal taxa. There is, however, a marked overall shift of sample positions in the copepod and macrofauna ordinations which is not evident in the nematode ordination, supporting the suggestion that the faunal differences between November and March are more a result of natural fluctuations in populations than of the effects of the Wheal Jane discharge.

Whereas nematodes live in the sediment, among the harpacticoids there are many epibenthic and tube-dwelling species, which might be expected to respond differently to pollution events than endobenthic species. Indeed, it is the absence of endobenthic species from Restronguet Creek that distinguishes the community in that creek. In the present study nematode community structure appears to change in an ordered fashion with increasing metal concentration established over historical time, and of the three components of the fauna (nematodes, copepods, macrofauna) examined the nematodes best reflect this gradient. The communities of copepods and macrofauna respond to the long-term metals gradient similarly, in that communities in Restronguet Creek are different from the rest but the communities in all the other creeks are not ordered according to the gradient, suggesting that other factors are influencing community structure in these creeks.

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