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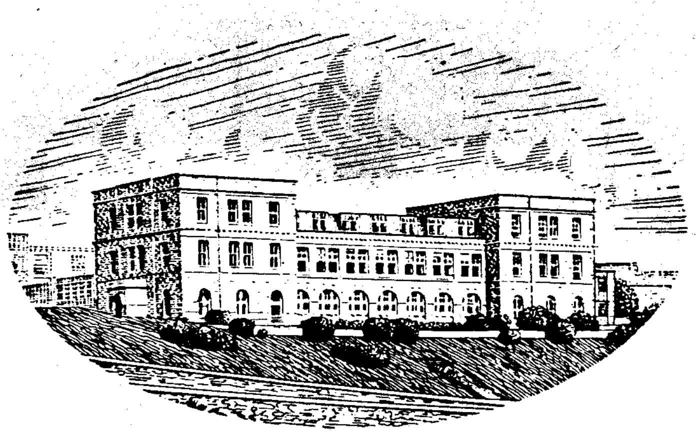

HEAVY METALS IN THE FAL ESTUARY, CORNWALL: A STUDY OF LONG-TERM CONTAMINATION BY MINING WASTE AND ITS EFFECTS ON ESTUARINE ORGANISMS.

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ABSTRACT

The Fal Estuary System in west Cornwall has, over many centuries, received inputs of heavy metals from various mining activities. In this context its most important tributary is the Carnon River, the acidic waters of which contain high concentrations of certain metals, notably Zn (mean concentration = 12400 μg/l), Fe (9473), Mn (1792), Cu (689), As (233) and Cd (25.6). The Carnon River drains into Restronguet Creek where estuarine mixing occurs and concentrations of dissolved Zn typically range from 100 to 2000 μg/l, Cu from 10 to 100 μg/l and Cd from 0.25 to 5.0 μg/l. The Creek sediments are highly contaminated, the levels of Cu, Zn, As and Sn being of the order of 1500 - 3500 μg/g.

Analyses of organisms from the Fal Estuary have shown that some species contain abnormally high concentrations of Cu, Zn and As, especially in those living in Restronguet Creek. Levels of Cu in certain species, for example *Fucus vesiculosus* and *Nereis diversicolor*, exceed 1000 μg/g, this level being two orders of magnitude higher than normal. However, tissue metal levels do not always reflect those of the environment: there is good evidence that some metals are regulated, including Zn, Cu, As, Mn and Fe, by particular species and in some cases these metals are utilised for specific purposes, for example, the hardening of the jaws of nereid and glycerid polychaetes. Cd is not usually regulated; although the dissolved Cd levels in Restronguet Creek are high, it is not accumulated appreciably by the biota, perhaps as a result of competition for uptake sites from other dissolved metals, especially Zn.

Experimental data indicate that the levels of Cu, Zn and recently-precipitated Fe oxide in the waters and sediments of Restronguet Creek would be expected to have a detrimental effect on the biota. Comparison of the Creek fauna with that of similar creeks in the Fal System shows the Creek supports only a sparse fauna; notably only one bivalve, *Scrobicularia plana*, survives within the creek and this population is confined to the margins. Evidently, bivalve larvae and juveniles are unable to withstand the toxic conditions. However, the flora and fauna is less obviously affected than might be predicted from experimental toxicity data. Several factors can be forwarded to explain this anomaly: first, the development of Cu or Zn tolerant strains in species such as *Nereis diversicolor* which enable the species to establish breeding populations within the Creek, and second, the development of increased tolerance with exposure to the conditions such as occurs when individuals are carried by tidal currents into the Creek.

Tolerant species often contain high concentrations of metals, particularly Cu; some of these species form the major food element of some predators inhabiting the Creek, such as fish and birds, which thereby have high metal intakes.

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CONTENTS

GENERAL INTRODUCTION

During the 19th century the metalliferous mining region of south-west England (Fig. 1) was one of the most important in the world and in its heyday the productions of Cu, Sn and As sometimes amounted to 50% of the world supply. Output declined rapidly towards the end of the century and of more than 1000 mines in the area described by Dines (1969) only a handful of Sn mines are at present operational. However, drainage from the old mine adits and erosion of the spoil heaps by water still continues and is reflected by the high concentrations of metals observed in the sediments and waters of many streams and estuaries in the area (Hosking et al., 1965; Hosking & Obial, 1966; Bryan & Hummerstone, 1971; Thornton et al., 1975).

Included among the most heavily contaminated estuaries are the Hayle (Cu), Gannel (Pb) and Looe (Ag, Pb), but the highest levels of Cu, As, and Zn occur in Restronguet Creek, a branch of the Fal Estuary System. Via the Carnon River the Creek drains parts of what was formerly the most productive of the south-western mining districts, that of St. Day, Redruth and Camborne (Dines, 1969). In addition to receiving wastes from deep mining for several hundred years, Restronguet Creek has an association with the recovery of alluvial Sn probably stretching back several thousand years to the bronze age (Graves-Morris, 1979). Stream tin was originally recovered from the Carnon Valley, but later operations gradually extended down into the upper reaches of the Creek itself. When, in the 19th century, the task of excluding the tide and removing the silt to reach the underlying Sn became too great, the metal was extracted by mining beneath the sediments of the Creek (Taylor, 1873; Barton, 1971). Until recently, alluvial Sn was still being recovered in the Carnon Valley; thus it is not surprising that Restronguet Creek appears to be silting up rapidly; in medieval times the Creek was reputed to be navigable as far as Bissoe (Barton, 1971) and 19th-century photographs show ore ships alongside quays at Devoran (Fig. 2) which are now almost inundated with the sediments. Other 19th-century activities, including the refining of arsenic in the Carnon Valley and the smelting of Pb and Sn alongside Penpol Creek, have also undoubtedly added to the overall levels of contamination (Barton, 1971).

When Cornish mining was at its peak, O'Shaughnessy (1866) reported that oysters in the Fal Estuary were green in colour through absorbing large amounts of copper from the contaminated water. When some of these oysters were exported to France, the presence of Cu in them was shown to be the cause of an outbreak of shellfish poisoning in Rochefort. The exact source of these oysters was not revealed, but green oysters from the vicinity of Restronguet Creek were studied by Boyce & Herdman (1898) and again by Orton (1923), who demonstrated that they were also contaminated with Zn and As. Analyses of sediments by the same author showed them to be heavily contaminated with As, Cu, Sn and Zn and this was confirmed more recently by Hosking & Obial (1966). The continued presence in Restronguet Creek of high sediment-metal concentrations and green oysters illustrates the long-standing nature of metal contamination in the area.

The present report describes observations on metal contamination in the Fal Estuary System carried out at intervals over the past 14 years.

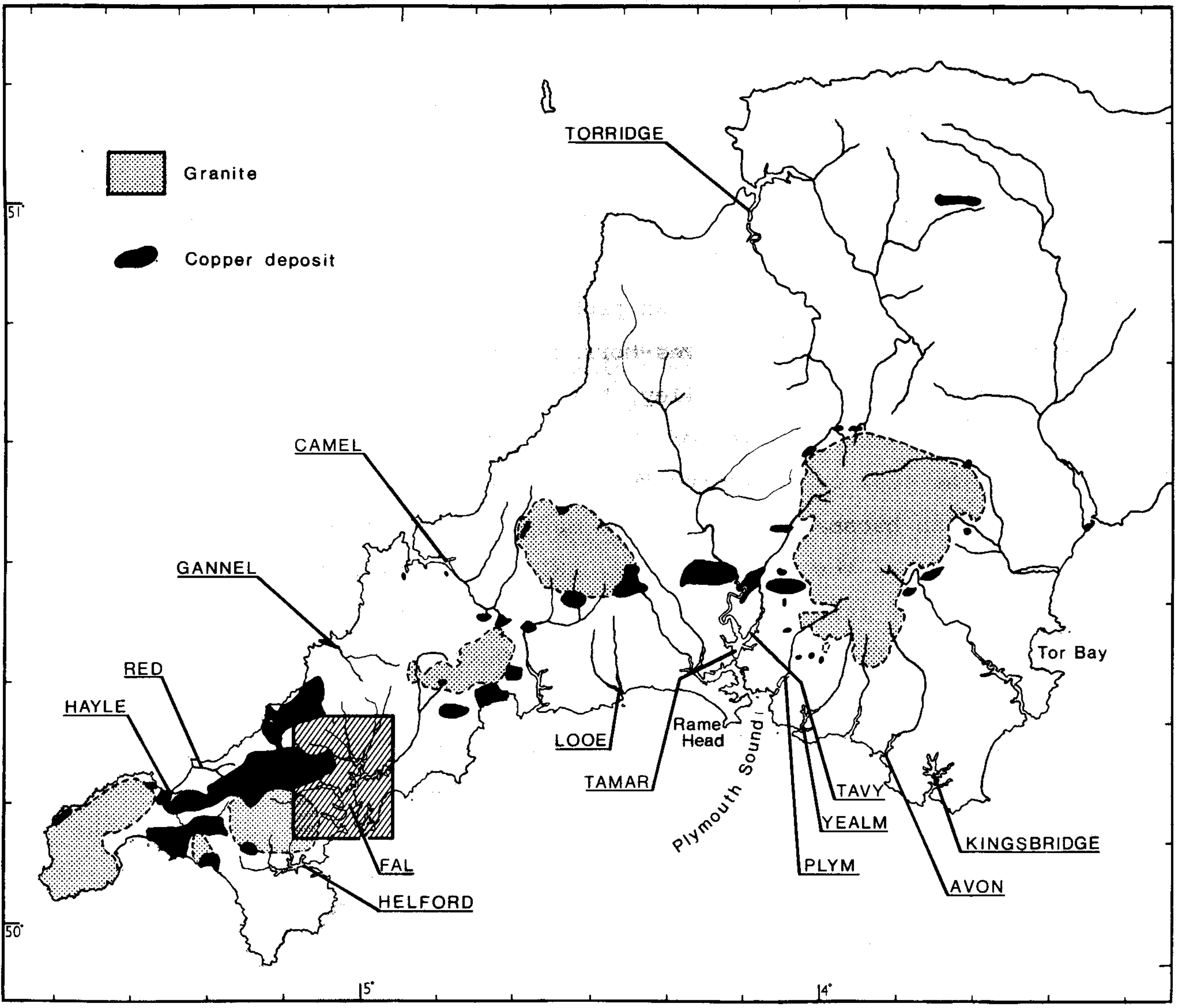

Fig. 1. South-West England: positions of estuaries and other features discussed in the text. Main study area is shaded and shown in greater detail in Figure 2.

Information from other contaminated and uncontaminated estuaries in the area has been used extensively to put conditions in the Fal Estuary into perspective. There are three main aspects to the Report : the first describes the input of metals to the area and some of the factors controlling their distribution in the environment; the second considers the bioaccumulation of metals by the macro-flora and fauna; the third covers observations on the biological effects of metals and their relation to the distribution of organisms in the estuary.

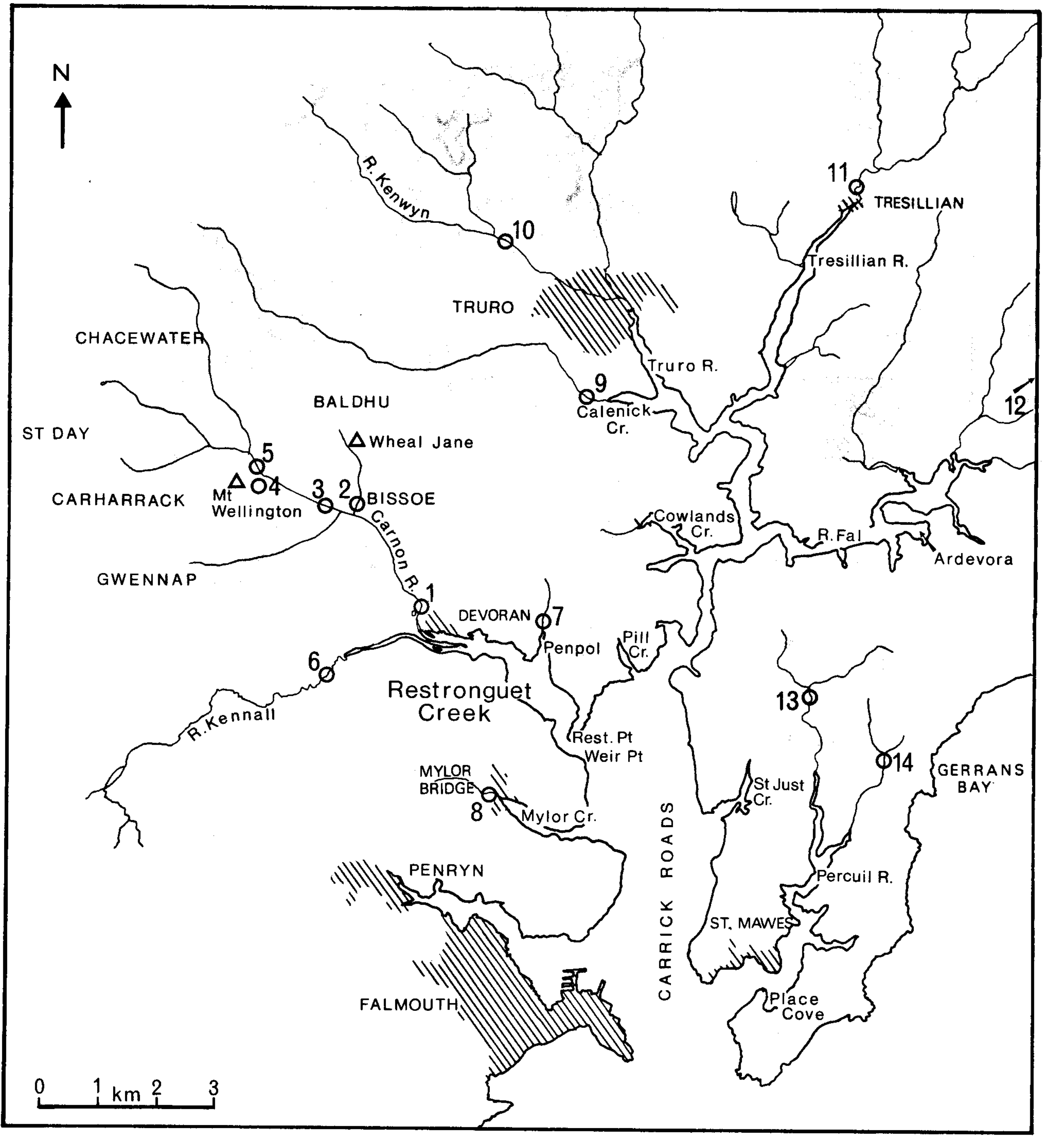

Fig. 2. Fal Estuary System: positions of freshwater sampling sites 1-14 on the Carnon River and other tributaries.

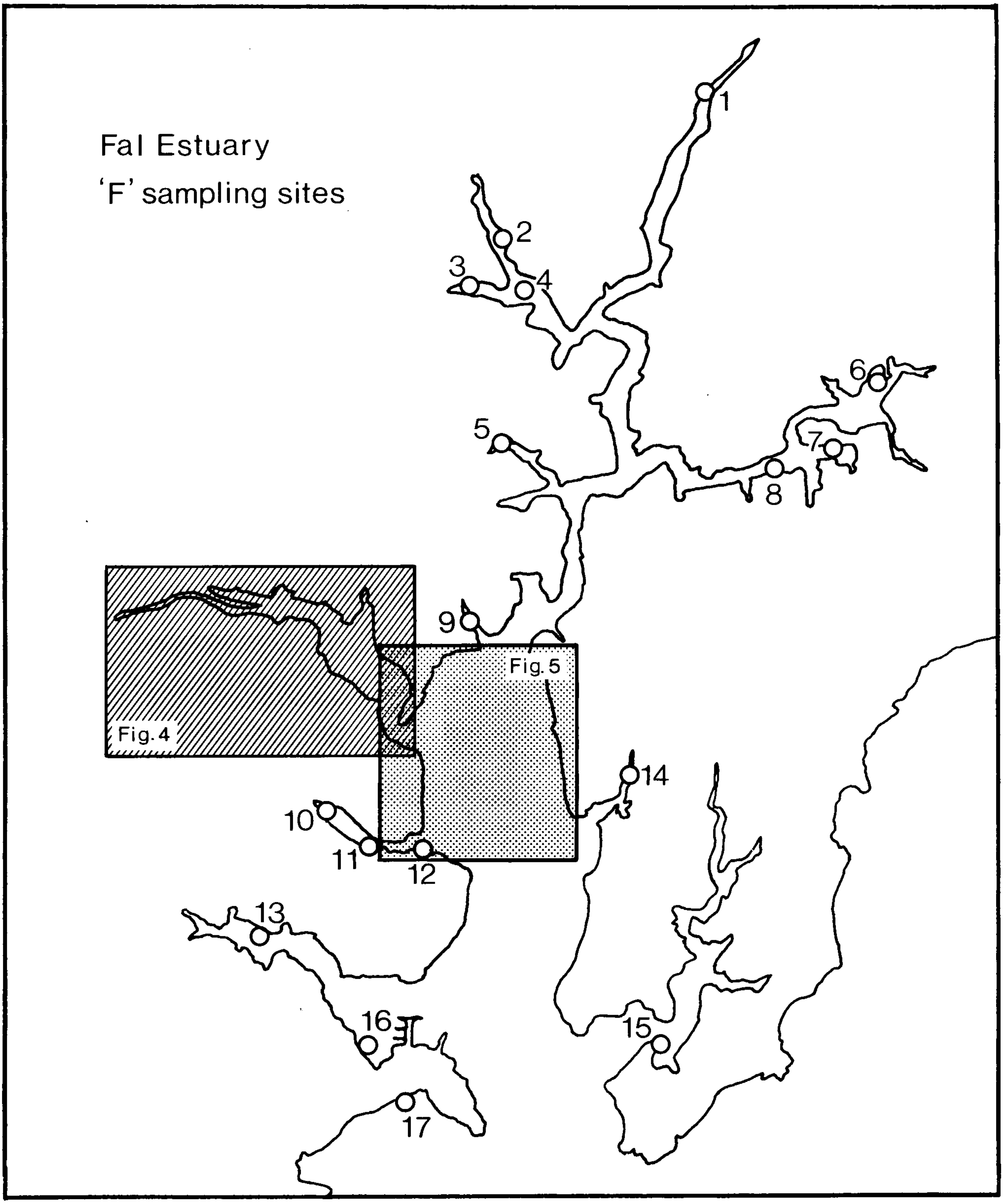

Fig. 3. Fal Estuary System: positions of 'F' sampling sites. Details of shaded areas are shown in Figures 4 & 5.

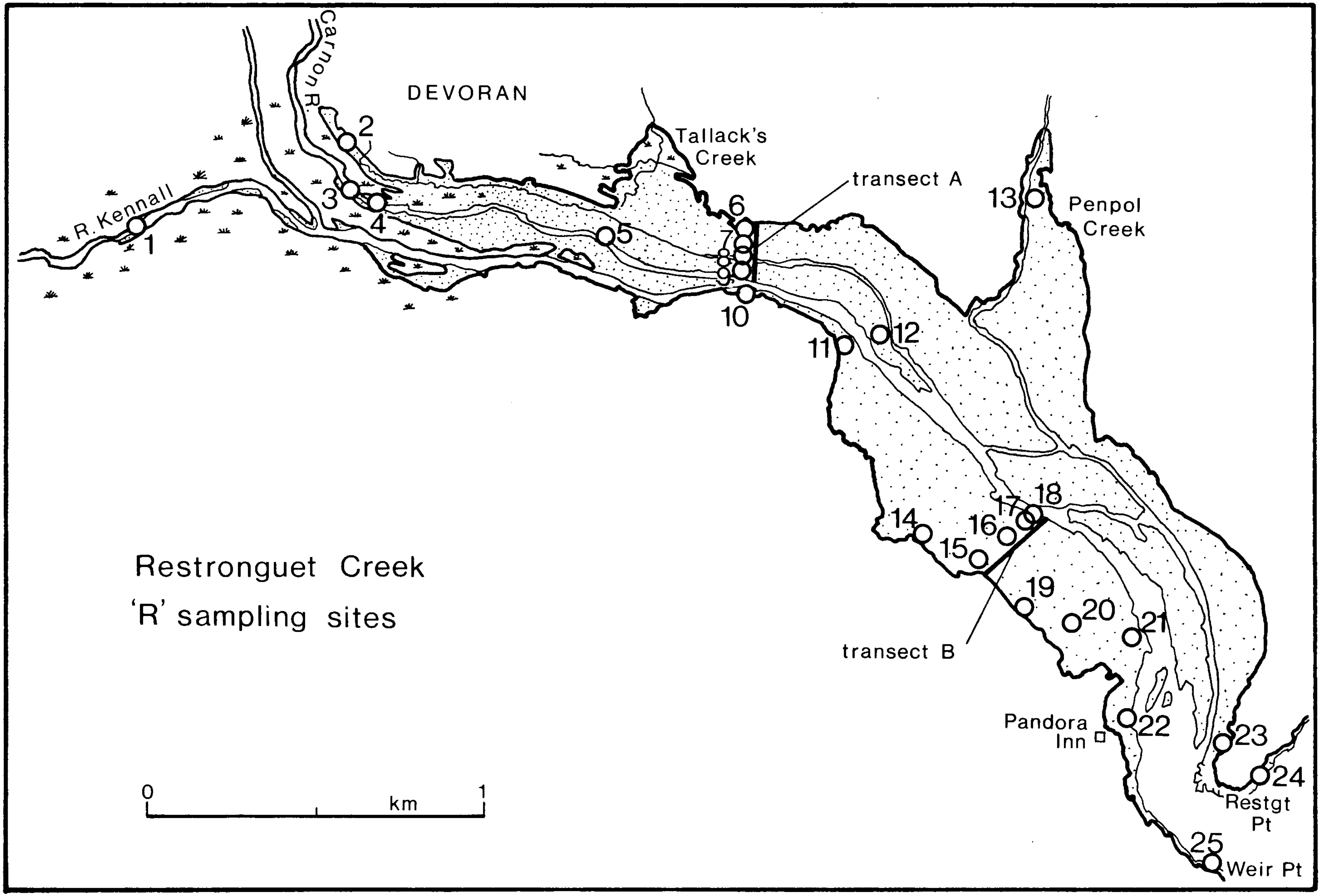

Fig. 4. Restronguet Creek: positions of 'R' sampling sites and 'A' and 'B' transects in the intertidal zone. Areas exposed during spring tides are stippled

METHODS

The basic techniques employed in this study have already been published, but additional information is given in the individual sections. Details of methods for the pre-cleaning and analysis of organisms for heavy metals are given in Bryan et al. (1980), and the treatment of sediment samples is described by Luoma & Bryan (1981). Samples of water were filtered (0.45 µm) as soon as possible after collection and acidified with HCl : high metal levels were determined by flame atomic absorption and low levels by direct injection into a carbon furnace (Perkin-Elmer 76B).

In laboratory experiments, filtered (0.45 µm) low-metal sea water from the English Channel was always used.

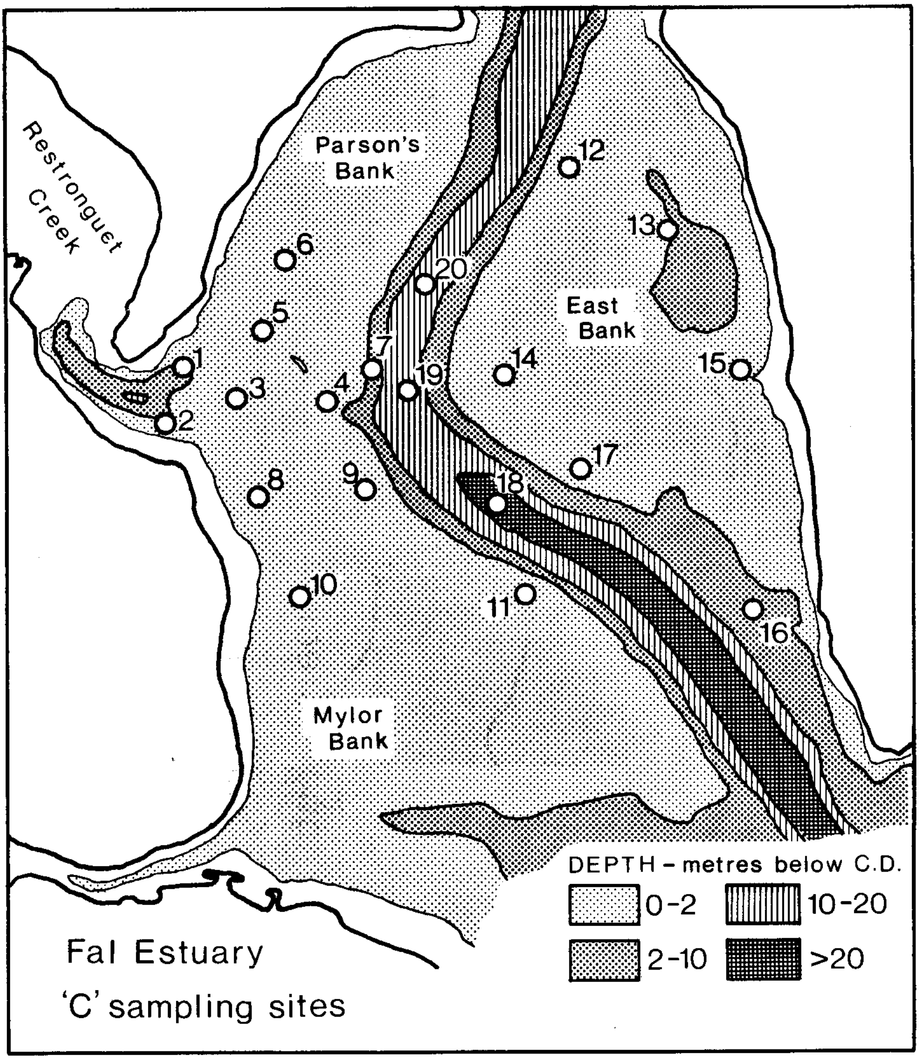

Fig. 5. Carrick Roads: positions and depths of 'C' dredge sampling sites off the mouth of Restronguet Creek.

HEAVY-METAL INPUTS TO RESTRONGUET CREEK AND FAL ESTUARY

Importance of the Carnon River

The principal source of heavy metals in Restronguet Creek is the Carnon River (Fig. 2) the catchment of which includes the Cu-and Sn-mining districts of Chacewater, St. Day, Carharrack, Gwennap and Baldhu (Hosking & Obial, 1966). Some mines were working in these localities in the seventeenth century and by the middle of the nineteenth they comprised one of the major copper-mining areas of the world. Copper production subsequently declined and by the turn of the century was almost negligible (Dewey, 1923).

Many of the old Cu mines are still drained by the County Adit (Fig. 2). Started in 1748 the Adit is some 30 miles long and joins the Carnon River at Mount Wellington Mine about 4 km from the head of Restronguet Creek (Barton, 1961). The acid (pH 4) adit water contains high concentrations of several metals, mainly in solution, and is a particularly important source of Cu (Table 1).

Mining for other metals, principally Sn, has continued intermittently in the Carnon Valley during the present century, the only active mine at present being Wheal Jane, although Mount Wellington mine reopened briefly in the nineteen seventies. The water draining from Wheal Jane, 2.5 km from the head of the Creek, contains a wide range of metals, the most significant being a high concentration of dissolved Zn (Table 1).

Until 1981, a plant at Bissoe recovered Sn from mine wastes which included tailings and alluvium carried down by the river and accumulated in the lower Carnon Valley. Particularly over the last 4 km of its course the Carnon River passes through ground dominated by metalliferous spoil heaps : being too toxic to support much vegetation, these are largely unprotected from erosion and thus provide additional inputs to the river.

Analyses of the Carnon River water before it enters Restronguet Creek show that it is quite acidic (pH 3.8) and contains high concentrations of Fe, Zn, Mn and Cu (Table 1; site 1). The last three named together with Cd are mainly in solution, but for As, Fe and Pb there is a significant insoluble component. A few determinations of metals not included in Table 1 have been carried out in water from site 1 and include 94000 µg/l of Na, 69000 µg/l of Ca, 10800 µg/l of Mg and 8820 µg/l of K. In addition, 6400 µg/l of Al were measured in the water

TABLE 1

CONCENTRATIONS OF METALS IN FRESHWATER INPUTS TO THE FAL ESTUARY SYSTEM

Total and filtered (0.45 µm) samples acidified immediately to 0.025 N with HCl

Highest values underlined. Samples taken 4 Aug. 82 except * - 21 Sept. 82 and ± - 20 Sept. 82

Sample site (No.) in Fig. 2	Soluble or Total	Carnon River µg/litre									
		As	Cd	Co	Cu	Fe	Mn	Ni	Pb	Zn	pH
(1) Road Bridge	Soluble	82	10.1	37	474	18500	2974	135	28	12030	3.8
	Total	200	9.9	60	493	29410	2971	135	39	12070	
(2) Wheal Jane	Soluble	22	24.5	52	2	44720	6889	142	31	25090	5.7
	Total	380	24.3	72	334	96730	7238	181	53	28560	
(3) Bissoe	Soluble	31	6.7	79	680	17210	1532	172	18	6900	3.8
	Total	30	6.5	111	684	17680	1528	167	18	6680	
(4) County Adit	Soluble	14	4.6	61	859	657	882	137	5.6	2868	4.1
	Total	24	4.6	224	864	1049	873	132	6.8	2774	
(5) Twelveheads	Soluble	58	1.2	ND	54	45	97	66	1.7	953	5.6
	Total	42	1.1	ND	53	137	94	47	2.1	929	
		Other freshwater inputs									
(6) Kennall	Total	3	ND	13	8	112	8	5	3	63	6.7
(7) Penpol	Total	11	ND	ND	9	129	72	26	3	27	6.8
(8) Mylor	Total	9	0.1	20	2	212	63	2	2	48	6.7
(8) Mylor*	Total	-	0.2	8	8	759	128	-	33	44	-
(9) Calenick*	Total	-	ND	7	14	744	139	-	15	130	-
(10) Kenwyn*	Total	-	ND	5	10	369	39	-	10	11	-
(11) Tresillian*	Total	-	ND	4	6	480	42	-	9	24	-
(12) Fal±	Total	-	0.7	6	9	1652	126	-	5	386	-
(13) Lanhoose±	Total	-	ND	6	2	209	3	-	11	171	-
(14) Tregassa±	Total	-	0.7	5	5	76	2	-	17	409	-
		Background water concentrations (Förstner & Wittmann, 1979)									
Fresh water		2	0.07	0.05	1.8	<30	<5	0.3	0.2	10	
Ocean sea water		2.1	0.01-0.07	0.04	0.04-0.1	1.3	0.2	0.2-0.7	0.001-0.005	0.01-0.62	

ND = not detectable by direct furnace AA

TABLE 2

ESTIMATES OF TOTAL METAL INPUT VIA CARNON RIVER

Analytical data for Sept. 80 - May 81 but
totals estimates for July 80 - June 81

			µg/litre			
As	Cd	Cu	Fe	Mn	Pb	Zn
Total concentrations and ranges						
233*	25.6	689	9473	1792	40†	12400
-	(6.5-106)	(421-977)	(5560-13900)	(971-3317)	-	(3630-57270)
Dissolved concentrations and ranges						
-	24.8	593	5024	1777	29	12470
	(6.4-106)	(370-973)	(2670-10360)	(955-3315)	-	(3630-57230)
Percentage dissolved metal						
-	96.9	86.0	53.0	99.2	72.0	100
Total annual input from July 80 - June 81 (metric tons)‡						
9.3*	0.76	20.4	280	53.0	1.18	367
Total annual input for 1971 (metric tons)‡						
5.5	0.71	21.3	253	33.4	1.38	262

*Langston (1983) †Fewer data; ‡Based on mean flow of 0.938 m^3/sec, kindly supplied by South West Water Authority

on one occasion of which about 15% was soluble; levels of Ag are usually below 1 µg/l, much of it being insoluble, and levels of Cr are of the same order. It is assumed that Sn occurs principally in suspension as the very insoluble oxide, cassiterite.

Metal concentrations in the Carnon River far exceed those of the similarly-sized River Kennall, which also enters the head of Restronguet Creek: levels in the stream entering at Penpol are also low (Table 1). Comparisons with other inputs to the Fal Estuary System (Table 1) suggest

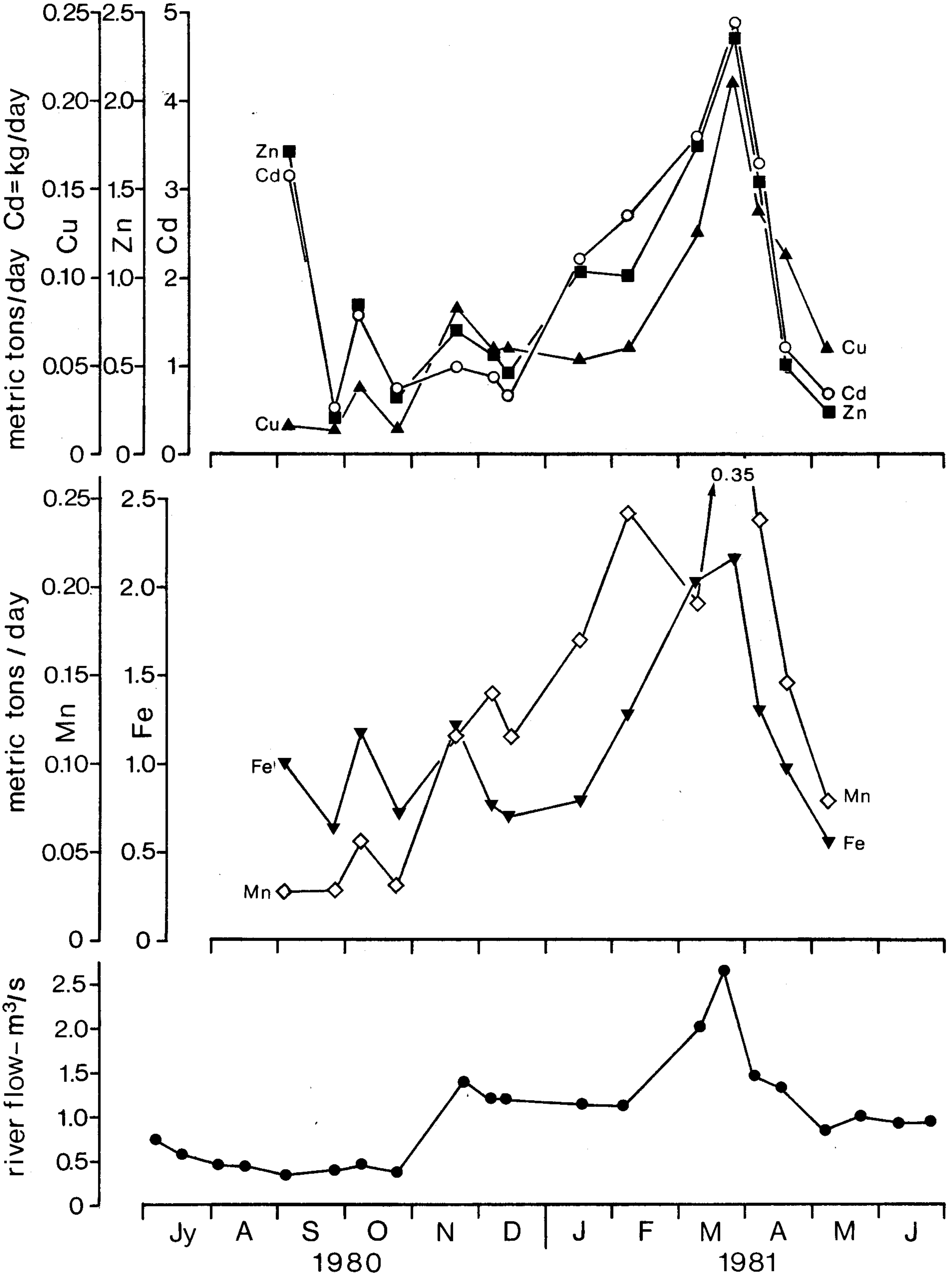

Fig. 6. Carnon River: variations in river flow and in total daily inputs of 5 metals. Flow data supplied by the South West Water Authority.

that even allowing for the greater flows of rivers such as the Fal, the Carnon River is, by a wide margin, the most important source of heavy metals in the system.

Table 2 shows the ranges and mean concentrations of total and dissolved metals in Carnon River samples collected in 1980-81. Concentrations of Cu, for which the County Adit is a major source, vary less than those of Zn and Cd which are presumably under the influence of mining activity at Wheal Jane (see Table 1). Figure 6 shows how rates of input varied for five metals during 1980-81. Clearly, the river flow rate is a major influence on input rates; however, concentration changes are also important and in September 1980 exceptional levels of Zn (57270 μg/l) and Cd (106 μg/l) produced input peaks when the river was low.

The annual input of metals between July 1980 and June 1981 is shown in Table 2 and a comparison with estimates from data for 1971 suggests that the present situation is not too different from that obtaining 10 years ago.

Fate of heavy metals in the Creek

On entering the Creek the Carnon River water flows over the denser sea water and, in calm weather, salinity stratification is very obvious. As the river water becomes mixed with sea water, the rise in salinity and pH leads to the flocculation of 'dissolved' Fe, probably as the hydrous oxide. Some other elements including Cu and As are associated with this process, and together with Fe tend to be removed from solution and deposited as sediment. On the other hand, Mn, Cd and Zn show much less evidence of removal from solution and their concentrations are largely dependent on the dilution of river water with sea water. Thus the dissolved concentrations of Mn, Cd and Zn are almost linearly related to salinity, and very little particulate metal is removed by filtration (Fig. 7). This contrasts with dissolved Fe, Cu and As (see Langston, 1983) where the formation of particulate material during mixing leads to more curved relationships (Fig. 7).

Because some metals tend to be deposited whilst others remain in solution, the relative proportions of metals in the Carnon River water and the Creek sediments differ appreciably. Assuming that 100% of the Fe in the Carnon River is retained by the Creek sediments, the percentage retention of other metals needed to produce the present sediment composition can be calculated. The results in Table 3 agree with the direct observations on the waters of the Creek and show that whilst only small percentages of Co, Cd, Mn, Ni and Zn in the River input are retained, much of the incoming Ag, As, Cu and Pb is deposited. Presumably Sn should be included with the latter group, since it occurs in the sediment mainly as cassiterite and must enter the Creek in this very insoluble form (Hosking & Obial, 1966).

Composition of the sediments

Surface sediments in Restronguet Creek are light brown in colour due to the deposition of iron oxides. Particle-size measurements (British Standard 1377) showed 80% to be less than 20 µm diameter and

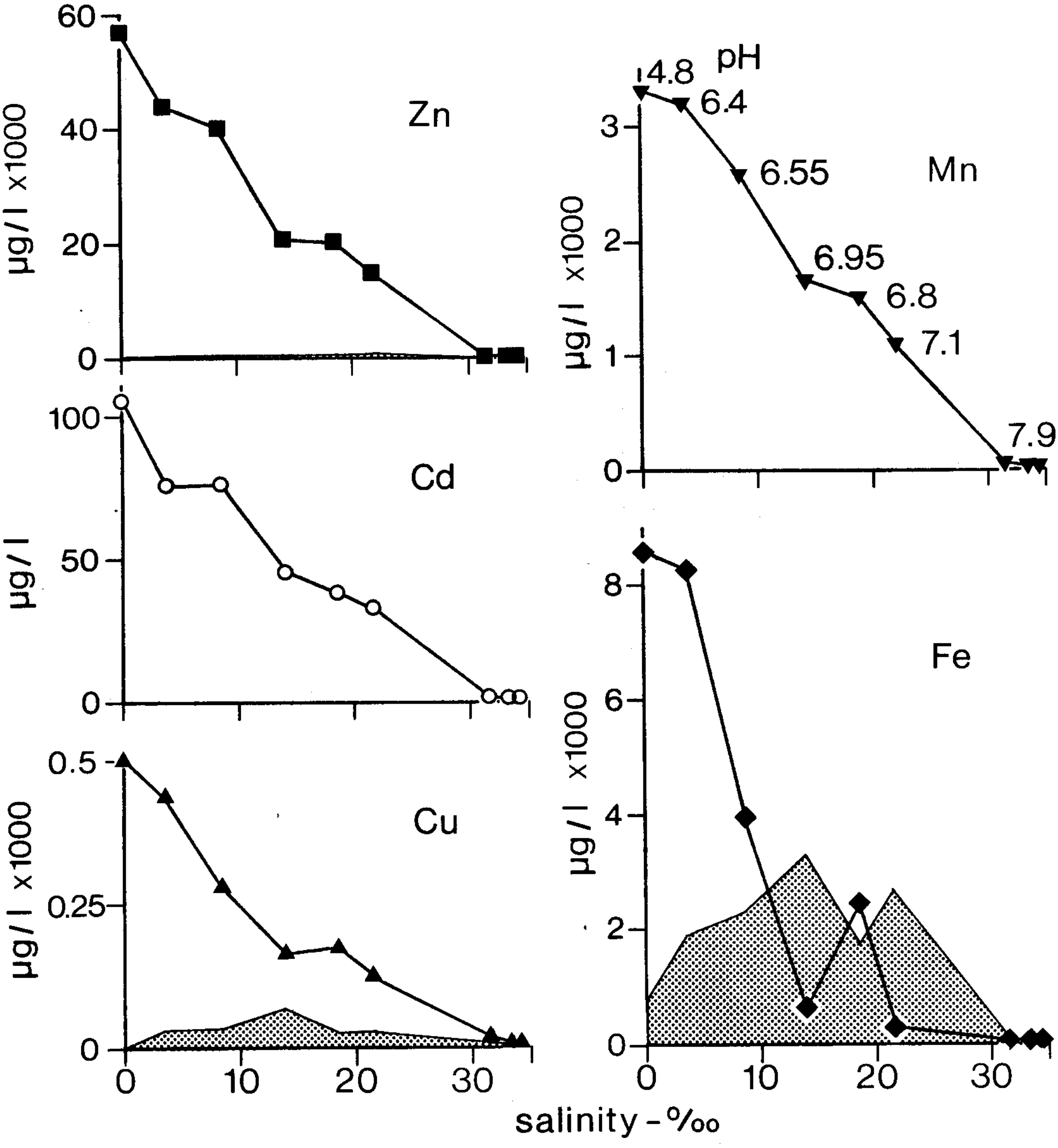

Fig. 7. Restronguet Creek: relationships between dissolved concentrations of 5 metals and salinity. Shaded areas represent particulate fractions of Fe, Cu and Zn, but were insignificant for Cd and Mn (4 Sept. 80).

TABLE 3

RELATIVE RETENTION OF METALS FROM CARNON RIVER BY RESTRONGUET CREEK SEDIMENTS

Ag	As	Cd	Co	Cu	Fe	Mn	Ni	Pb	Zn
River water concentrations (μg/litre) from Tables 1 and 2									
0.45*	233	25.6	60	689	9473	1792	135	40	12400
Predicted sediment concentrations (μg/g) if all metals in River deposited and sediment Fe = 5.6%									
2.66	1377	151	355	4073	5.6%	10593	786	229	73303
Mean observed sediment concentrations (μg/g) (from Bryan et al., 1980)									
3.46*	1732	1.1	18	2148	5.6%	475	31	297	2700
Percentage of metals in River retained by sediments if Fe = 100%									
130	126	0.7	5	53	100	4.5	3.9	130	3.7

*Mean of 2 values

40% less than 5 μm. The organic content is about 6% and the low Ca level shows that the sediment contains at most only a few percent of $CaCO_3$ (Table 4).

In Table 4 metal concentrations in the Creek sediments are compared with those from other parts of the Fal Estuary. The results compare favourably with those of other workers (Orton, 1923; Hosking & Obial, 1966; Yim, 1972; Thornton et al., 1975) and show clearly that the Creek is the most heavily contaminated part of the Fal Estuary System. The influence of the Creek inputs on surface-sediment concentrations of Cu and Zn is shown diagrammatically in Figure 8. An interesting feature is the occurrence of very metallic sediments in Mylor Creek which lies to the south of Restronguet. The river input to Mylor Creek is small (Table 1) and the sediments clearly have their origin in the Restronguet input. Hosking and Obial (1966) noted the tendency for highly metallic water to persist between the two Creeks with little evidence of eastward migration. This

TABLE 4

TYPICAL ANALYSES OF SURFACE SEDIMENTS COLLECTED IN FAL ESTUARY SYSTEM (1976-80)

Positions of sites are shown in Figs. 3,4,5, . Highest values are underlined.

Results are for nitric acid digest of <100 µm fraction, but fusion used for Sn (Bryan *et al.*, 1980)

‡Ca soluble in 1N-HCl; *see Luoma and Bryan (1981)

Estuary	Site	Concentration (µg/g) except Fe (%)													% Ca‡	% Organic matter*
		Ag	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Sn	Zn		
		Restronguet Creek														
Restronguet Cr.	R1	2.8	1076	0.9	14	21	1733	4.75	0.24	401	25	204	2672	1587	0.25	8.2
	R6	4.1	2520	1.2	22	37	2540	5.76	0.22	559	32	290	1730	3515	0.55	5.8
	R13	3.5	1600	1.3	18	23	2170	6.30	0.45	466	37	396	1350	3000	0.50	5.8
	R16	3.0	-	1.1	21	25	2145	5.39	-	571	26	220	-	2866	1.50	-
	R22	2.6	-	1.5	16	29	1785	3.92		441	27	198	-	1978	1.66	5.0
		Other parts of Fal System														
Carrick Rds	C1	1.9	-	0.5	15	35	1808	4.73	-	406	27	201	-	1781	-	-
	C20	0.9	-	0.6	9	36	490	2.49	-	254	23	119	-	494	-	5.5
	C9	0.8	-	0.2	7	31	341	2.29	-	254	20	91	-	380	-	-
Penryn Cr.	F13	0.7	-	0.3	12	47	322	3.70	-	432	38	219	-	440	-	-
Mylor Cr.	F10	2.0	-	1.2	12	32	1117	3.45	-	393	29	179	-	980	0.80	6.2
Cowlands Cr.	F5	0.4	-	0.4	9	25	195	2.74	-	344	20	85	-	361	0.37	5.4
Pill Cr.	F9	0.8	-	0.2	11	43	527	3.42		252	34	219	-	613	-	-
Calenick Cr.	F4	2.0	120	1.0	6	25	335	2.57	0.43	172	17	137	700	628	0.31	3.9
Truro R.	F2	2.7	-	1.1	8	43	344	2.76	-	214	27	220	-	759	-	5.4
Tresillian R.	F1	1.1	88	1.0	8	23	256	2.21	0.61	260	21	100	591	400	-	4.9
R. Fal	F8	0.4	56	0.4	3	15	129	1.21	0.20	116	9	48	125	252	-	1.9
St Just Cr.	F14	0.6	-	1.3	9	32	356	3.10	-	260	25	97	-	508	0.69	7.3
Place Cove	F15	0.1	-	0.1	7	21.5	31	2.24	-	281	23	30	-	106	4.30	1.6
		Other contaminated estuaries														
Hayle	(upper)	1.3	550	0.6	28	36	782	5.15	0.06	742	32	218	1750	942	3.10	4.4
Gannel	(upper)	2.9	233	3.0	40	29	217	3.32	0.09	1160	49	2175	305	1215	5.60	3.0
Tamar	(upper)	0.9	85	1.5	23	44	305	2.81	0.90	758	49	156	101	392	0.40	7.6
		Control estuaries														
Yealm	(upper)	0.2	34	0.3	11	26	35	2.73	0.82	368	25	50	126	110	-	4.6
Avon	(mid)	0.1	13	0.3	10	37	19	1.94	0.12	417	28	39	28	98	-	4.2
Ratio: Restronguet max./Avon		41	194	4.3	2.2	1.0	134	3.2	3.7	1.3	1.3	10	95	36		

tendency for metallic conditions to be confined to the western side of the Carrick Roads may also explain the presence of relatively high sediment levels in Pill Creek and Penryn Creek. Additional inputs of metals from various sources in the Truro and Calenick areas probably explain the relatively high levels of sediment zinc at the head of the Truro River. The generally lower concentrations in the Fal branch of the system may be the result of dilution with china clay wastes borne by the River Fal from the St. Austell area. Hosking *et al.* (1965) have drawn attention to the apparent failure of china clay wastes to adsorb Zn and thus assist in its deposition from the relatively high concentrations (386 µg/l; Table 1) in the waters of the River Fal.

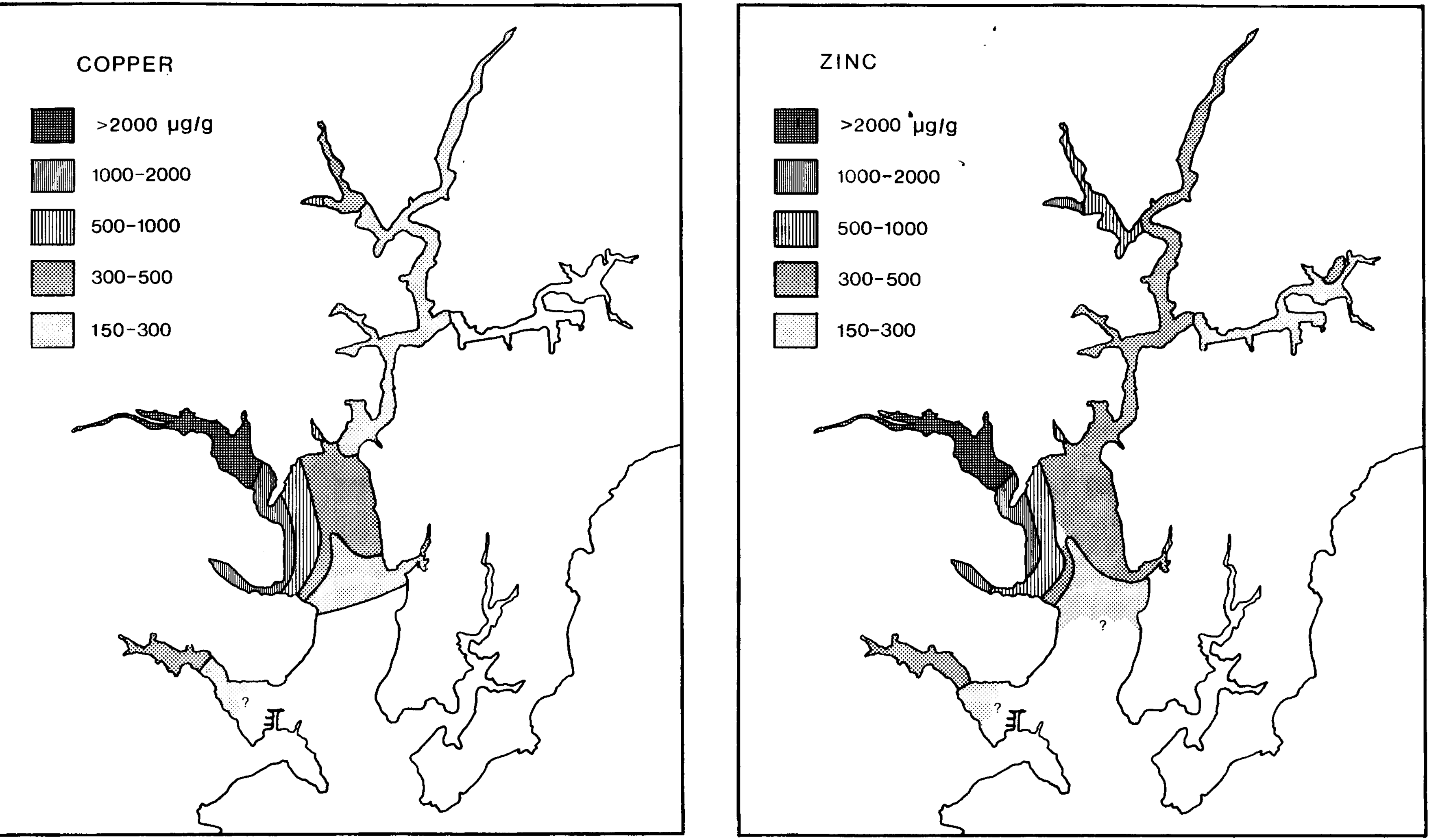

Fig. 8. Fal Estuary System: approximate distributions of Cu and Zn in <100 µm fraction of surface sediment (HNO_3 digested).

Compared with other estuaries contaminated by mining, such as the Hayle, Gannel and Tamar (Table 4), Restronguet Creek is most notable for its high levels of As, Cu and Zn, the contrast being less marked for Ag and Sn. The bottom line in Table 4 shows that the highest Creek values for As, Cu and Sn exceed those of the uncontaminated Avon Estuary by about two orders of magnitude, and a factor of about 40 separates the levels of Ag and Zn.

Conditions to which organisms are exposed in Restronguet Creek

Water

The hydrography of the Creek has not been investigated in detail but some observations on the chemistry of the water, related to the tidal cycle of conditions experienced by the biota, can be outlined.

At low tide the fresh water issuing from the Carnon and Kennall Rivers is channelled down the centre of the Creek and joined by several minor tributaries, notably from Penpol. On spring tides, most of the Creek bed is exposed at low tide but on neap tides a considerable area of the lower estuary remains immersed. On the flood tide the river water mixes with the sea water but being less dense forms a brackish layer on the surface of the incoming wedge of sea water, creating a marked vertical salinity gradient. This feature is well illustrated by some measurements made on 22 Mar. 71 at high tide: opposite Devoran (Fig. 4) the salinity of the surface layer (top 5 cm) was 0.86^{o}/oo and at 40 cm depth the salinity was 23.0^{o}/oo; on the same occasion, near transect A these values were 7.9 and 29.8^{o}/oo respectively.

Because the waters of the Creek are tidal and usually highly stratified, it is difficult to ascribe certain water concentrations to specific localities. Larval organisms at the sediment surface are likely to be vulnerable to even brief exposure to the very high metal concentrations which occur in the less saline surface waters. Thus on two occasions, one very calm and the other with a NW breeze blowing down the valley, samples were collected at the water's edge on the incoming tide along two transects A and B (Fig. 4). On both transects the clam *Scrobicularia plana* occurs only at the highest site, whereas the polychaete *Nereis diversicolor* is more widely distributed. The results for dissolved Zn and Cu in Figure 9 show that, as might be expected, the concentrations generally fall with distance from the river channel. In addition, particularly at transect B the decline in concentration was

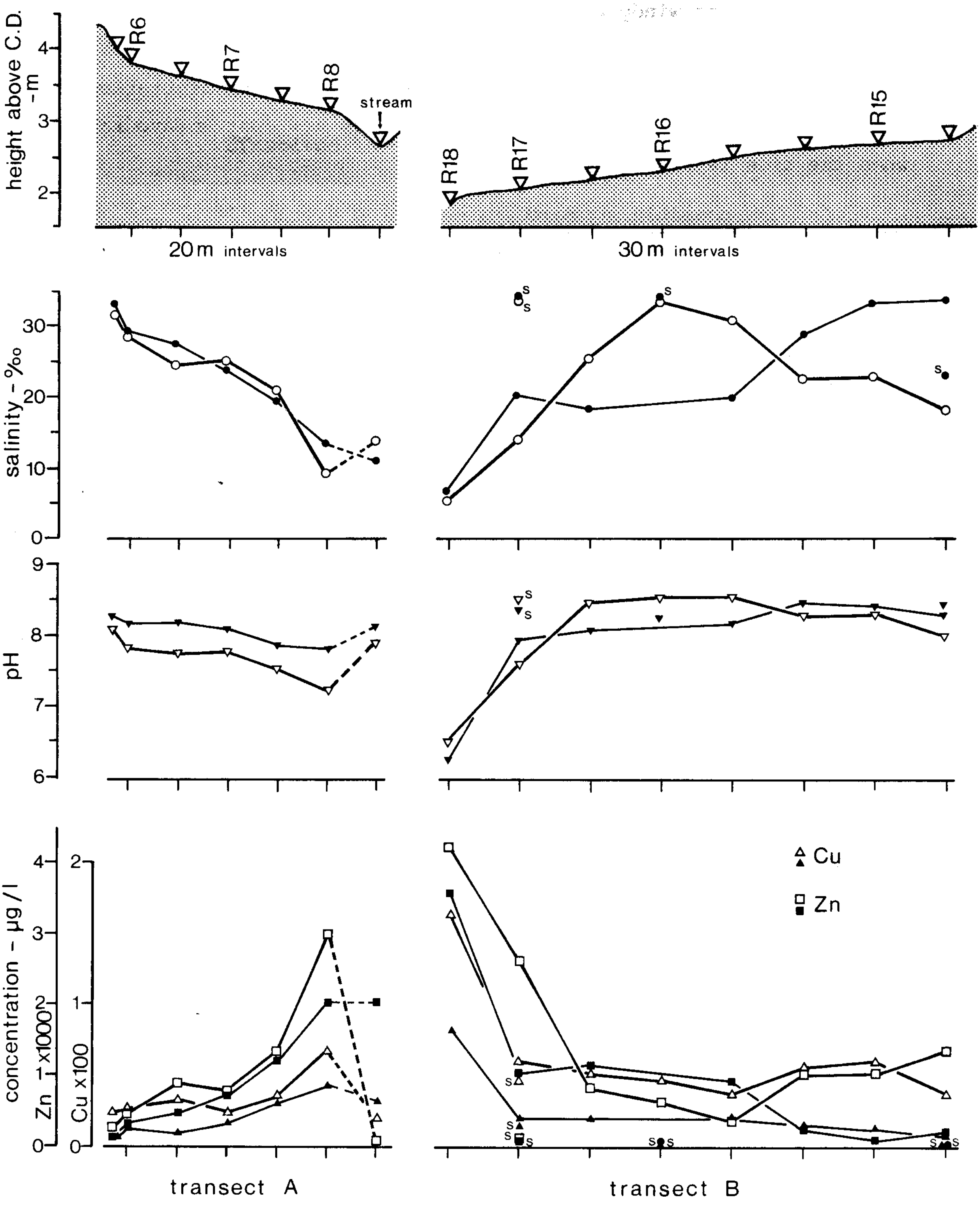

Fig. 9. Restronguet Creek: salinity, pH and dissolved Cu and Zn at the water's edge as tide advances across mudflats at transects A and B in Figure 4. Open symbols, calm weather (6 July 79); closed symbols, windy weather (19 July 79). (S) refers to samples of standing water collected before advance of tide. On transect A, low metal levels on lower shore reflect dilution, with low-metal stream water.

most obvious when windy conditions increased mixing. Samples taken from pools of standing water which remained from the previous tide were generally of high salinity and relatively low metal concentration : this suggests that the conditions on the mud flats are most unfavourable when the tide is rising.

Another possible approach to assessing average levels in the waters of Creek is to assume that the salinity of the sediment pore water, below the immediate surface layer, reflects the average salinity of the overlying water. The salinity at site R5 (Fig. 4) in March, when inputs of water and metals are high, was about 25°/oo (Table 5) and from Figure 7 is equivalent to about 10000 µg/l of Zn and 100 µg/l of Cu. However, the concentrations of Zn (and Cd) shown in Figure 7 are exceptional and a more realistic value for Zn would be in the area of 1000-2000 µg/l. Near the mouth of the Creek, concentrations would be expected to be 10 times lower (100-200 µg/l of Zn, 10 µg/l of Cu). This is borne out by the work of Boyden _et_ _al_. (1979) who sampled surface and bottom waters at low tide and high tide near the mouth of the Creek on four occasions during 1972-73. In surface waters, Zn values were 28-300 µg/l and Cu 5-26 µg/l. Bottom water values were 17-192 µg/l for Zn and 5-25 µg/l for Cu. A comparison with the baseline concentrations for sea water in Table 1 demonstrates that,even in the lower reaches of the Creek,metal levels are extremely high.

Sediment

Table 5 shows that sediment-metal concentrations in soft mud decline only slightly in a downstream direction. However, lower concentrations are found in sandy areas near the mouth of the Creek (site R21). Sediment concentrations remain fairly constant down to a depth of 20 cm, although analyses of a longer core at site R2 showed that at a depth of 60-65 cm the level of Cu was double that at the surface. What period of time is represented by 65 cm of deposition can only be guessed but may be of the order of 100y and would therefore cover the final demise of the Cu mines.

The upstream limit of the deposit-feeding clam _Scrobicularia plana_ occurs at the uppermost site (R6) on transect A (Fig. 4) and animals transplanted to sediment farther down the shore do not survive (p. 85). Along this transect, metal concentrations in surface sediments generally decrease with distance from the main channel (Table 6) and so also do the percentages of metals extracted from the sediments with hydrochloric

TABLE 5

METAL CONCENTRATIONS IN SEDIMENT CORES FROM RESTRONGUET CREEK

Unsieved sediment digested with nitric acid and residue dissolved in dilute hydrochloric acid

Site and Date	Depth (cm)	Interstitial Salinity (‰)	Concentration (µg/g) except Fe (%)				
			Cu	Fe	Mn	Pb	Zn
(R1)	0 - 5	5.2	3200	6.09	437	393	2290
Mar. 71	5 - 10	6.6	3480	5.69	373	388	2770
	10 - 15	10.6	2960	5.26	345	314	2410
	15 - 20	11.1	3080	6.29	389	320	2300
(R2)	0 - 5	19.7	3520	6.51	412	385	2730
Jan. 71	5 - 10	17.8	3610	6.36	414	359	2800
	10 - 15	20.5	3600	6.17	420	372	2920
	15 - 20	23.8	3690	5.88	422	421	2930
(R5)	0 - 5	25.6	3560	6.85	432	417	2800
Mar. 71	5 - 10	25.2	3750	6.67	510	579	3290
	10 - 15	28.3	3500	5.58	431	394	3160
	15 - 20	29.6	2930	5.15	527	839	2010
(R20)	0 - 5	35.0	2480	4.93	331	319	1780
Dec. 70	5 - 10	30.4	2960	5.99	438	-	1640
	10 - 15	28.2	3750	7.47	541	-	2320
	15 - 20	24.5	3730	8.35	708	-	2660
(R21) Dec. 70	Coarse red sand (surface)	-	546	3.72	338	205	735

acid, acetic acid or ammonium acetate solution. Thus the potential availability of surface-sediment metals decreases with increasing distance from the river channel more markedly than the total concentration (Table 6). This might be expected, since the sediments on the upper shore are almost certainly older than those near the River Channel. Other work at site R6 showed that 1N ammonia extracts humic materials and 399 µg/g of Cu from the surface sediment and this suggests that a significant fraction of the metal is organically-bound.

Measurements of metals in the interstitial waters of these sediments (Table 6) show that concentrations of Zn and Cu in the oxidized surface sediment are such as might be expected if they are influenced by levels in the overlying water (e.g. Fig. 9). Below depths of 1-2 cm negative Eh values are found: the lower levels of dissolved Cu and Zn in the deeper, black sediments indicate their removal, possibly as sulphides, whereas the

TABLE 6

EXTRACTABILITY OF METALS FROM SURFACE SEDIMENTS ON

TRANSECT 'A', AND INTERSTITIAL WATER CONCENTRATIONS

Site on transect 'B'	Sediment extractant*	Sediment concentration (µg/g)				Depth (cm)	Interstitial water concentration (µg/litre)			
		Cu	Fe	Mn	Zn		Cu	Fe	Mn	Zn
(R6) Upper shore (_S_. _plana_)	HNO_3 (conc.)	2541	57600	559	3515	0	66	150	406	262
	HCl (1N)	1920 (76%)	21800 (38%)	143 (26%)	2850 (81%)	10	30	8530	294	216
	HAc (25%)	1534 (60%)	8600 (15%)	134 (24%)	3248 (92%)					
	AmAc (1N)	90 (3%)	8 (0.01%)	24 (4%)	185 (5%)					
(R7) Middle shore (_N_. _diversicolor_)	HNO_3 (conc.)	2607	56400	579	4153	0	56	129	436	396
						10	7	8800	445	104
(R9) 5 metres from Carnon R. channel (no macrofauna)	HNO_3 (conc.)	2568	76700	595	5414	0	83	106	520	390
	HCl (1N)	2110 (82%)	54000 (70%)	276 (46%)	4730 (87%)	10	16	8920	350	67
	HAc (25%)	2039 (79%)	33200 (43%)	295 (50%)	5354 (99%)					
	AmAc (1N)	239 (9%)	13 (0.02%)	68 (11%)	440 (8%)					

*Luoma & Bryan (1981)

high concentrations of Fe probably reflect the reduction and dissolution of Fe oxides.

Summary

The principal input of heavy metals to Restronguet Creek and the Fal Estuary System is the Carnon River which receives drainage from various sources associated with metalliferous mining and extraction processes.

Carnon River water is acidic (pH ∿ 3.8) and contains high average concentrations of Zn (12400 µg/l), Mn (1792), Cu (689) and Cd (25.6) of which 86-100% is in solution. Levels of Fe (9473) and As (233) are also high and roughly 50% is dissolved. Changes in metal inputs are mainly controlled by the river flow rate, but fluctuations in concentrations of Zn and Cd are sometimes important. Usually inputs are highest in the period November - April and reach maxima of about 2.5 metric tons/d for Zn and more than 0.2 for Cu, although the average levels are about 1 metric ton/d for Zn and 0.06 for Cu.

On mixing with sea water in Restronguet Creek, the behaviour of dissolved Cd and Mn from the Carnon River is almost perfectly conservative and that of Zn slightly less so. Thus water having a salinity of 25°/oo may contain more than 1000 μg/l of dissolved Zn. Co and Ni also tend to remain in solution. Iron, on the other hand, rapidly flocculates and other elements tending to be removed from solution and therefore enriched in the sediments include Ag, As, Cu and Pb. Throughout all these processes, Sn probably exists largely as particles of cassiterite.

Restronguet Creek sediments contain levels of As, Cu and Sn (∿ 2500 μg/g) which are two orders of magnitude higher than normal, whilst levels of Ag (4 μg/g) and Zn (3500 μg/g) are roughly 40 times normal. Apart from Sn, which occurs mainly as the very insoluble oxide cassiterite, these metals are readily extractable from the surface sediments and are therefore potentially bioavailable. In addition, the interstitial water in surface sediments contains significant levels of Cu and Zn.

In Restronguet Creek, the potential availability of heavy metals appears to fall with increasing distance from the head of the Creek and also with distance laterally from the Carnon River channel. Widespread metal contamination also occurs beyond the mouth of Restronguet Creek and is particularly obvious in the Carrick Roads and Mylor Creek.

The next section considers the bioaccumulation of metals by organisms in Restronguet Creek and compares the concentrations in their tissues with those of organisms from other parts of the Fal System and from other estuaries.

CONCENTRATIONS OF HEAVY METALS IN THE FLORA AND FAUNA

Introduction

In the following sections, concentrations of heavy metals in organisms from Restronguet Creek are compared with values from other parts of the Fal Estuary System and from other estuaries in south-west England. The locations of estuaries and sampling sites in the Fal System are given in Figures 1-5.

Several important points need to be stressed in considering these results:

(1) Different types of organisms absorb metals from different sources: dissolved metals are accumulated by many species, but sediment-bound metals may be absorbed by deposit-feeding organisms and, particularly in larger animals, dietary sources may be pre-eminent. The total concentrations of metals in these various sources may not necessarily reflect their availability to organisms since this also depends on the chemical speciation of the metal.

(2) Concentrations accumulated by organisms do not always change in relation to the availability of metals in the environment. In algae and some animals an approximately direct relationship does exist for a range of metals. However, other species are able to regulate the concentrations of some metals against environmental changes and this is more likely to occur if the element has an essential biochemical role. Some metals in this category enter the Fal Estuary System in appreciable quantities, notably Zn, Fe, Cu and Mn.

(3) Metal levels that may be regarded as 'normal' vary, sometimes considerably, between species. Thus a concentration which in one organism would be considered unexceptional, might reflect gross contamination in another.

(4) At a single sampling site, metal levels in an organism may change in response to factors such as time of year, size, age or reproductive condition. An attempt has been made in the present work to compare organisms of similar size, although this is not always possible.

Macroflora

Brown algae

Fucus vesiculosus is widely distributed within the Fal System and

TABLE 7

BROWN SEAWEEDS: CONCENTRATIONS IN WEED FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Highest concentrations underlined

Estuary	Site	Date	Ag	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
			Fucus vesiculosus (sample excludes growing tips) µg/g dry wt									
			Restronguet Creek									
Restronguet Cr.	R10	Apr. 81	2.21	1.41	15.7	4.7	1450	13500	533	9.6	68.1	4200
	R11	Apr. 81	1.17	0.99	6.7	3.5	938	6190	156	7.7	37.4	3230
	R12	Apr. 81	0.60	0.95	4.9	2.8	919	6290	68	7.1	28.3	2710
	R14	Apr. 81	0.79	0.81	3.8	1.6	777	2030	134	4.2	15.6	2440
	R19	Apr. 81	1.17	0.91	20.3	2.2	717	2240	61	4.3	18.5	2670
Weir Pt	R25	Apr. 81	0.31	0.93	5.5	1.7	190	536	125	4.4	6.6	2190
			Other parts of Fal System									
Truro R.	F2	-	1.05	1.11	2.4	1.7	85	1840	205	3.2	26.4	563
Calenick Cr.	F3	Apr. 80	0.99	1.45	3.1	3.3	210	2508	279	4.8	57.1	788
Tresillian R.	F1	Jan. 80	0.28	0.90	2.4	3.4	56	1550	306	2.9	14.5	585
Cowlands Cr.	F5	Apr. 80	0.18	0.93	3.7	2.0	32	3270	672	2.4	15.7	475
Pill Cr.	F9	June 76	0.42	0.75	3.8	2.8	119	1263	144	3.4	24.8	556
St Just Cr.	F14	May 80	0.22	1.11	5.3	4.0	94	1640	171	4.9	20.9	1180
Mylor Cr.	F11	Mar. 80	0.52	0.81	4.0	4.8	302	2045	124	2.6	21.6	1120
Mylor Cr.	F10	Mar. 80	0.48	0.76	2.6	2.2	250	1333	68	1.8	13.6	1010
Penryn Cr.	F13	Jul. 76	0.43	0.84	3.6	2.1	70	715	172	7.3	19.5	429
Falmouth	F17	June 76	0.27	1.00	0.6	0.8	7	57	51	2.2	10.7	94
			Other contaminated localities									
Hayle	(upper)	Apr. 77	0.81	2.27	3.5	4.6	436	4808	149	21.7	32.3	1864
Red River	(mouth)	Mar. 74	0.33	0.17	-	-	389	660	279	-	6.3	919
Tamar	(mid)	May 82	0.24	0.81	2.3	7.7	27	631	78	1.6	10.5	113
			Control estuaries									
Looe	(mouth)	Mar. 76	0.37	1.39	0.6	0.6	8	121	94	6.2	3.1	104
Torridge	(Appledore)	May 80	0.29	1.18	2.3	2.2	10	746	193	11.4	4.5	99

Estuary	Site	Date	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
			Ascophyllum nodosum (2nd vesicle from tip + first internode analysed)							
Restronguet Cr.	R14	Aug. 79	0.79	0.24	546	129	29	1.5	2.3	1400
	R19	Jul. 79	0.93	0.09	375	136	103	1.4	1.6	1690
Pandora Inn	R22	Jul. 79	0.61	0.05	372	170	19	0.7	2.9	1070
Weir Pt	R25	Jul. 79	0.67	0.31	424	355	35	0.9	2.5	1660
			Other parts of Fal System							
Mylor H.	F12	Jul. 79	0.50	0.20	138	75	19	0.6	1.4	1010
Falmouth	F17	Jul. 79	0.25	0.03	8	37	9	0.6	0.8	106

penetrates into the upper reaches of Restronguet Creek beyond site R10. Ascophyllum nodosum is less tolerant of low salinity but penetrates to site R14 in the middle reaches of the Creek. Table 7 shows that samples of both species from the Creek contain concentrations of Cu exceeding by roughly two orders of magnitude those of weed from site F17 at the mouth of the Estuary. Similarly, more than an order of magnitude separates levels of Zn in weed from the two localities. In F. vesiculosus, despite cleaning, a proportion of metals in weed from the Creek can be attributed to contamination of the fronds with sediment particles. If it is assumed that, at worst, all the Fe in the weed stems from contamination with particulates, then the percentages attributable to contamination with other metals can be calculated from the composition of the local sediment: at site R10 these amount to about 20% for Cd, Mn and Zn, 30-40% for Ag, Co and Cu, 80% for Ni and over 90% for Pb and Cr. In A. nodosum from the Creek, metal concentrations, including that of Fe, are usually lower than in F. vesiculosus. It seems likely, therefore, that particulate contamination in F. vesiculosus accounts for some of the differences between the two species. No values for As are given in Table 7, but Langston (1980) found 63-160 µg/g in F. vesiculosus from Restronguet Creek compared with about 15 µg/g in 'normal' weed. In addition, Klumpp & Petersen (1979) reported 38-184 µg/g in F. vesiculosus, 33-93 µg/g in A. nodosum and 15-114 µg/g in Enteromorpha.

Based on earlier results from the Fal System, Bryan & Hummerstone (1973a) concluded that concentrations of metals such as Cu and Zn in F. vesiculosus give a reasonable reflection of their availabilities in solution. There is, however, some evidence from later work that Cu and Pb, for which fucoid polyphenols have very high selectivity coefficients, may also be scavenged by the weed directly from suspended particles (Luoma et al., 1982).

Vascular plants

Salicornia, a salt-marsh plant, colonises many of the higher mudflats and in the upper reaches of the Creek (site R3) must be exposed to high concentrations of dissolved metals in addition to those in the sediments. Levels of Cu, Fe, Mn and Zn in the roots exceed those in the shoots and, in both tissues, concentrations are much higher in plants from the Creek than in those from an uncontaminated estuary (Table 8).

Macrofauna

Coelenterates

Actinia equina and Tealia felina from the Creek are comparatively uncontaminated (Table 9), although it is difficult to see how these

TABLE 8

SALICORNIA SP.: COMPARISON OF CONCENTRATIONS IN RESTRONGUET CREEK WITH THOSE FROM AVON ESTUARY (JULY 1971)

Samples and sites	µg/g dry wt Cu	Fe	Mn	Zn
Roots				
Restronguet Cr. (∿ R3)	571	4517	73	372
(R6)	611	7779	117	359
Avon Estuary (mid)	16	558	20	34
Shoots				
Restronguet Cr. (∿ R3)	168	3168	49	289
(R6)	169	1879	56	161
Avon Estuary (mid)	12	219	18	62

TABLE 9

CONCENTRATIONS IN SEA ANEMONES FROM RESTRONGUET CREEK COMPARED WITH THOSE FROM OTHER AREAS

			µg/g dry wt			
	As	Cd	Cu	Fe	Mn	Zn
Actinia equina						
Restronguet Cr. (R15)	-	-	15.4	142	8.0	177
S. Devon coast	-	0.23	10.3	278	9.8	185
Tealia felina						
Restronguet Cr. (R24)*	55	0.40	7.7	-	-	289
Southampton Water[‡]	72	0.07	-	-	-	200
Irish sea[†]	-	0.66	57.0	730	9.3	280

*Klumpp & Petersen (1979); Leatherland and Burton (1974)

[†] Riley & Segar (1970)

anemones could avoid exposure to high ambient concentrations of Cu and Zn. The results imply that the metals are regulated, although more work is necessary to confirm this.

Polychaete Worms

Nereis diversicolor is probably the commonest and most widely distributed member of the Creek macrofauna and worms in the upper reaches of the Creek contain very high levels of Cu. Surprisingly, however, the highest concentrations, sometimes exceeding 2000 µg/g, occur in worms at site R1 in the Kennall branch of the Creek, where the freshwater input is low in metals, rather than in the more obviously contaminated parts of the Creek such as site R4 on the bank of the Carnon River (Table 10).

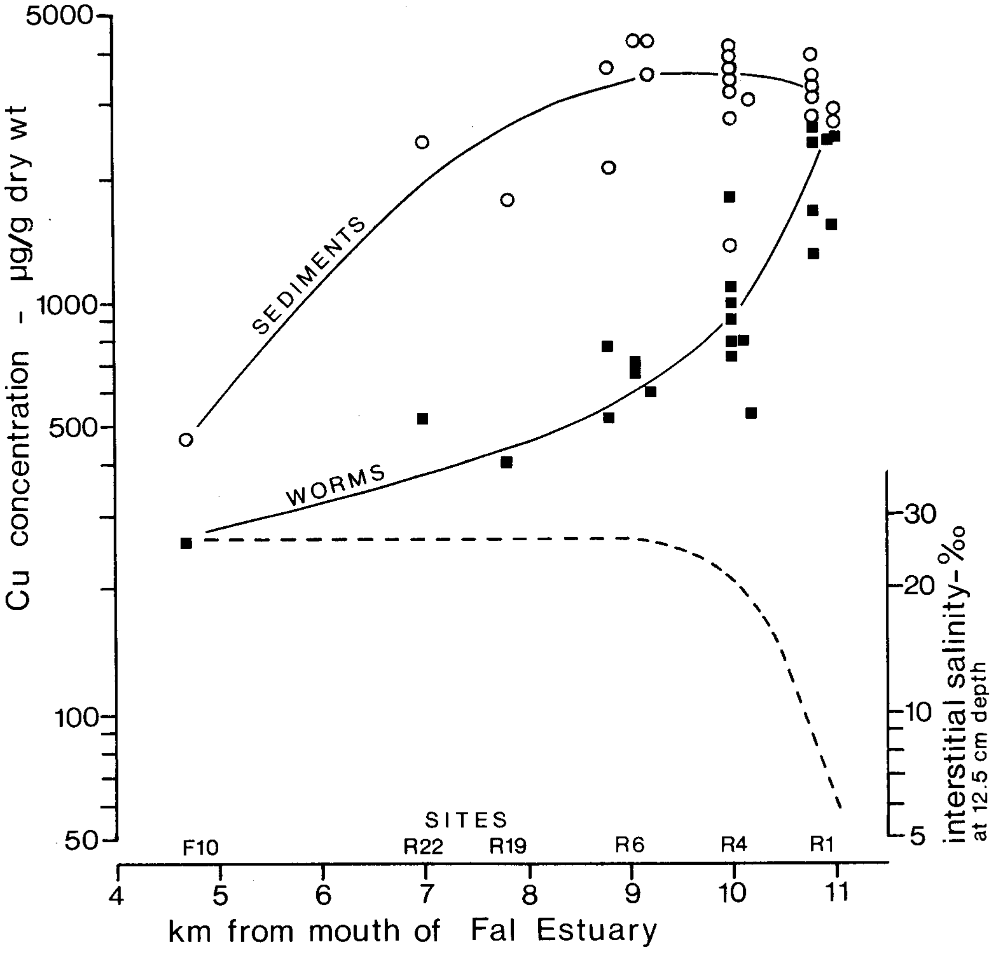

Fig. 10. Nereis diversicolor: changes in concentrations of Cu in worms and sediments (HNO_3 digest) with distance along Restronguet Creek. Positions of sites are shown in Figs. 3 & 4. Broken line shows sediment salinity (after Bryan & Hummerstone, 1971).

TABLE 10

NEREIS DIVERSICOLOR: CONCENTRATIONS IN WORMS FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Highest concentrations underlined

Estuary	Site	Date	Ag	As*	Cd	Co	Cr	Cu	Fe	Hg*	Mn	Ni	Pb	Sn*	Zn
			µg/g dry wt.												
			Restronguet Creek												
Restronguet Cr	R1	Mar. 77	6.0	23	0.53	11	0.6	1430	554	0.05	12.0	2.3	5.2	0.16	262
	R4	May 78	3.7	-	1.8	14.2	0.3	630	439	-	8.3	6.5	1.9	-	405
	R6	Mar. 77	3.0	87	0.81	4.5	0.4	832	378	0.23	12.3	3.6	4.0	-	318
Penpol	R13	Mar. 77	6.2	57	0.97	7.5	0.7	932	268	0.18	14.1	3.9	9.8	0.46	302
Pandora Inn	R22	June 76	1.6	-	0.44	5.3	0.6	271	364		15.2	4.6	3.7	-	146
			Other parts of Fal System												
Truro Riv.	F2	Dec. 74	9.5	-	1.44	7.3	<0.3	196	424	-	6.9	5.3	3.1	-	389
Calenick Cr.	F3	Apr. 80	25.1	-	2.34	5.4	0.4	372	549	-	9.4	4.6	7.7	-	258
Tresillian Riv.	F1	Jan. 80	1.5	15	1.3	6.9	-	84	735	0.21	11.9	-	2.7	1.6	298
River Fal	F7	May 80	0.8	-	1.2	6.7	0.2	40	333	-	10.1	3.9	0.8	-	259
Cowlands Cr.	F5	Apr. 80	0.9	-	0.17	4.9	0.2	59	497	-	18.1	3.2	2.2	-	218
Pill Cr.	F9	June 76	0.8	-	0.25	1.8	0.8	73	355		6.5	2.1	2.2		142
St Just Cr.	F14	May 80	0.3		0.71	1.4	0.13	44	284	-	10.4	1.9	2.2	-	156
Mylor Cr.	F11	Mar. 80	1.5		0.77	4.6	0.55	243	509		12.1	3.0	4.5	-	237
Mylor Cr.	F10	Mar. 80	2.8		0.91	4.2	0.05	298	379		11.7	3.4	2.8		208
Penryn Cr.	F13	July 76	0.4		0.05	2.8	0.31	18	294		10.3	1.9	8.9		120
			Other contaminated estuaries												
Hayle	(upper)	Nov. 74	5.3	84	0.47	10.3	<0.3	1210	734	0.22	5.7	9.1	4.2	0.08	260
Tamar	(upper)	Nov. 74	0.6	13	0.53	8.0	<0.3	130	591	0.14	12.8	4.3	7.0	0.34	179
			Control estuaries												
Torridge	(lower)	Jan. 80	0.3	14	0.44	7.6	<0.3	21	604	0.28	13.9	4.4	2.0	0.09	163
Avon	(mid)	Dec. 77	0.1	7	0.14	5.1	0.5	19	564	0.07	11.8	3.3	5.4	0.09	197

*analyses done between 1978-80 (Bryan et al., 1980)

Concentrations of Cu in sediments from the two localities are similar and the difference between the worms may in some way be related to salinity, that in the Kennall sediment being 5-11°/oo compared with about 20°/oo at site R4 (Bryan & Hummerstone, 1971). The overall effect is that concentrations of Cu in worms from the Creek fall rather more rapidly downstream than do the sediment levels (Fig. 10).

Appreciable concentrations of Cu are also found in N. diversicolor from other parts of the Fal system, including Calenick Creek and Mylor Creek, and in other localities in south-west England, particularly the Hayle Estuary (Table 10). Results from a large number of estuaries have shown that, generally, a remarkably good relation exists between Cu levels in the ragworm and those of sediment samples digested with nitric acid or extracted with 1N hydrochloric acid (Luoma & Bryan, 1982).

N. diversicolor from the Creek also contain abnormally high levels of Ag and As (Table 10) which can be related to the high sediment concentrations (Bryan, 1974; Langston, 1980). On the other hand, despite the high concentrations of other metals in the waters (Zn, Mn, Cd) and sediments (Sn, Fe, Zn), levels in N. diversicolor from the Creek are comparatively 'normal'. Reasons for this include the ability of the ragworm to regulate concentrations of Zn, Mn and Fe in its soft tissues and also, for Zn, the presence of a high level in the jaws (∿ 1.5%) which appears unrelated to environmental levels and in normal worms amounts to perhaps 25% of the body burden (Bryan & Hummerstone, 1973b, 1973c; Bryan & Gibbs, 1980). The limited accumulation of dissolved Cd by the ragworm probably results from competition from Zn for uptake sites, and was observed experimentally by Bryan & Hummerstone (1973b). Failure of the worm to absorb much Sn probably reflects its occurrence in the sediments largely as the insoluble oxide cassiterite.

Perinereis cultrifera is less tolerant of low salinities than N. diversicolor and occurs in coarse deposits in the lower reaches of

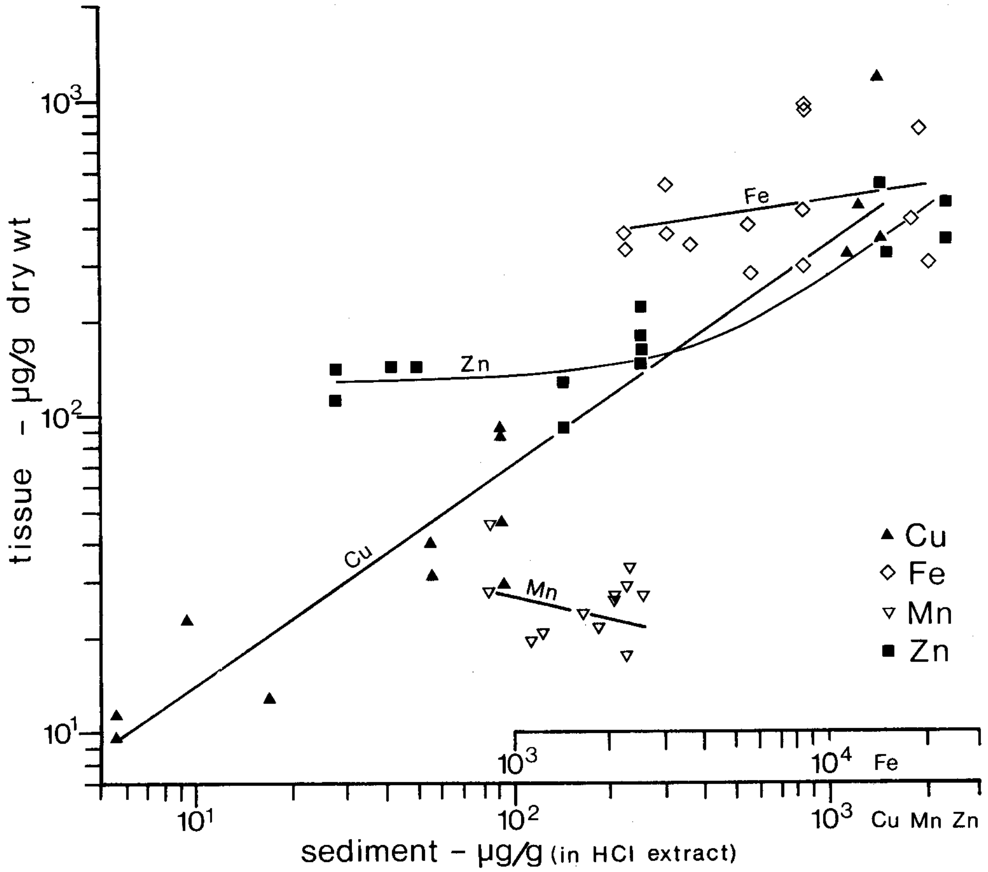

Fig. 11. Perinereis cultrifera: relationships between tissue concentrations and those of 1N HCl extracts of the < 100 μm fraction of surface sediment.

TABLE 11

CONCENTRATIONS IN ERRANT POLYCHAETES FROM FAL ESTUARY SYSTEM COMPARED WITH VALUES FROM OTHER LOCALITIES

Highest concentrations underlined

Estuary	Site	Ag	Cd	Cu	Fe	Mn	Pb	Zn
		Perinereis cultrifera (µg/g dry wt)						
		Restronguet Creek						
Pandora Inn	R22	-	-	1210	-	21	-	489
Restronguet Pt	R23	7.2	1.1	687	691	20	5.5	784
Weir Pt	R25	-	-	329	424	21	1.8	551
		Other parts of Fal System						
Place Cove	F15	0.4	0.4	38	282	28	1.8	130
		Other estuaries						
Kingsbridge	(Salcombe)	0.3	0.9	12	380	26	2.4	142
Yealm	(lower)	0.3	1.5	12	347	24	-	146
		Nephtys hombergi (µg/g dry wt)						
		Ag	Cd	Cu	Fe	Mn	Pb	Zn
		Restronguet Creek						
Restronguet Cr.	R6	3.3	0.6	2227	3263	7.5	44.7	518
Pandora Inn	R22	1.7	0.3	646	1720	12.6	-	353
		Other parts of Fal System						
Cowlands Cr.	F5	0.5	0.7	75	830	12.9	3.5	274
Place Cove	F15	0.2	-	47	622	8.1	-	252
		Other estuaries						
Tamar	(lower)	0.4	0.3	51	1361	10.0	7.3	256
Kingsbridge	(Salcombe)	0.5	1.9	36	364	5.4	3.7	268
		Glycera convoluta (µg/g dry wt)						
		Ag	Cd	Cu	Fe	Mn	Pb	Zn
		Restronguet Creek						
Penpol	R13	-	-	440	1371	17.2	-	298
Pandora Inn	R22	-	-	828	1360	-	-	483
		Other parts of Fal System						
St Just Cr.	F14	-	-	45	954	8.8	-	169
Place Cove	F15	0.5	-	64	1064	9.4	-	240
		Other localities						
Torbay		-	-	42	934	7.9	-	299
Whitsand Bay		-	-	70	783	4.2	-	292

Restronguet Creek. At site R22, for example, metal levels in P. cultrifera generally exceed those of N. diversicolor but, if anything, the reverse is true of concentrations at uncontaminated sites (Tables 10 & 11). Relationships between tissue concentrations and those of sediment extracts are shown in Fig. 11. As with N. diversicolor, body-Cu levels are clearly related to those of the sediments, whereas concentrations of Fe and Mn show signs of being regulated against environmental changes. Similarly, Zn appears to be regulated at low or moderate sediment concentrations but, at the high levels found in the lower Creek, control is less effective in P. cultrifera than in N. diversicolor.

Nephtys hombergi from sites R6 and R22 in the middle and lower reaches of the Creek contains appreciably higher concentrations of Cu, Fe and Zn than comparable samples of N. diversicolor (Tables 10 & 11). In these high-Cu worms the head end is blackened and X-ray microanalysis indicates that this is caused by the deposition of Cu sulphide in the body wall. A surface coating of oxide may account for the high level of Fe in the Creek animals. As in nereid polychaetes, concentrations of Cu in N. hombergi reflect environmental differences far more obviously than do body levels of Zn or Mn.

Glycera convoluta, a carnivorous polychaete, is found occasionally in the Creek and, as with the previous species, contains abnormally high levels of Cu but less obviously enhanced concentrations of Zn and other metals (Table 11). In uncontaminated G. convoluta about half of the body-Cu is found in the jaws (Gibbs & Bryan, 1980). Copper levels in the jaws of worms from the Creek are unaffected by the environment and thus their contribution to the body burden of Cu falls to a few percent. It is thought that Cu may be essential to harden the jaws of glycerid worms, and in G. gigantea the jaw tips contain 130,000 µg/g (13%) of the metal.

Cirriformia tentaculata occurs at site R22 in the lower part of Restronguet Creek (R22), near the low water mark, and contains higher-than-normal levels of Cu and Zn, but not Fe or Mn (Table 12).

Tharyx marioni collected from the same area of the Creek as C. tentaculata contains a remarkable level of As (Table 12). However, this feature seems to be unrelated to the high level of As in the Creek sediments, since equally-high concentrations are found in worms from uncontaminated sites

TABLE 12

CONCENTRATIONS IN SEDENTARY POLYCHAETES FROM FAL ESTUARY SYSTEM COMPARED WITH VALUES FROM OTHER LOCALITIES

Highest concentrations underlined

Estuary	Site	Ag	As*	Cd	Cu	Fe	Mn	Zn
		male *Cirriformia tentaculata* (µg/g dry wt)						
		Restronguet Creek						
Pandora Inn	R22	0.50	-	0.4	194	752	6.8	176
		Other parts of Fal System						
Place Cove	F15	0.04	84.0	-	15	702	15.2	71
		Other estuaries						
Tamar	(lower)	0.51	-	-	37	841	13.4	82
Yealm	(lower)	0.13	-	0.2	22	954	6.7	63
		Tharyx marioni (µg/g dry wt)						
		Ag	As*	Cd	Cu	Fe	Mn	Zn
		Restronguet Creek						
Pandora Inn	R22	-	2335	-	262	1183	13.4	81
		Other parts of Fal system						
Place Cove	F15	-	1512	-	161	1818	19.2	138
		Other estuaries						
Tamar	(lower)	-	2275	-	148	1602	14.2	53
Yealm	(lower)	-	2183	-	84	1091	13.6	51
		Melinna palmata (µg/g dry wt)						
		Ag	As*	Cd	Cu	Fe	Mn	Zn
		Fal system						
Carrick Rds	C5	-	-	-	3124	558	19.8	122
	C4	-	-	-	2042	520	22.0	116
Calenick Cr.	F4	3.6	-	-	498	663	16.4	119
Cowlands Cr.	F5	1.9	-	-	560	835	19.9	149
Place Cove	F15	0.7	26	-	314	410	13.6	121
		Other estuaries						
Tamar	(lower)	0.2	-	-	662	744	17.3	90
Rame Head	(coastal)	3.2	-	-	882	270	17.4	115

*Gibbs et al. (1983)

(Gibbs et al., 1983). Especially high levels of As, exceeding 10000 µg/g, are found in the extensible feeding palps of T. marioni, but its biochemical role is uncertain.

Levels of Cu are significantly increased in worms from the Creek, but those of Zn, Fe and Mn appear relatively 'normal' and are presumed to be regulated.

Melinna palmata dredged from the Carrick Roads off the mouth of Restronguet Creek contains a high level of Cu (Table 12). Whilst some of this Cu may be a reflection of the high ambient levels in the area, worms from uncontaminated localities, some of them offshore, also contain large amounts of Cu. Around 10000 µg/g of Cu, amounting to 30-40% of the body burden, are found in the branchiae and its accumulation is thought to function as a chemical defence against predation (Gibbs et al., 1981).

Evidence for Zn, Fe and Mn in M. palmata (Table 12) shows little difference between levels in Carrick Roads animals and those from less-contaminated or offshore sites, again suggesting that these metals are regulated.

Polychaete summary

The presence of high levels of Cu in the waters and sediments of Restronguet Creek and adjacent parts of the Fal Estuary is generally reflected by the presence of higher concentrations of Cu in polychaete worms. In species like Nereis diversicolor and Nephtys hombergi, which penetrate farthest upstream, Cu concentrations can reach 100 times 'normal'. In the lower reaches of the Creek, Cu levels in some species (Perinereis cultrifera and Glycera convoluta) may still be 10 - 100 times 'normal', but in the sedentary polychaetes Cirriformia tentaculata, Tharyx marioni and Mellina palmata the increases are less obvious. Where they have been measured in worms from the Creek, levels of Ag are abnormally high: so also are values for As in N. diversicolor, but not in T. marioni in which exceptionally high concentrations are the norm. Although, generally speaking, levels of Zn and Fe are higher in polychaetes from the Creek, by comparison with Cu, increases are relatively small suggesting that these metals, together with Mn, are fairly efficiently regulated.

TABLE 13

SCROBICULARIA PLANA: TISSUE CONCENTRATIONS AT RESTRONGUET CREEK

SITE R13 (MARCH 80)

Tissue (6 clams)	µg/g dry wt Cu	Fe	Mn	Zn
Digestive gland	101	1925	25	7270
Kidney	168	1655	14	866
Mantle and siphons	56	2051	11.0	547
Gills	48	1218	9.5	912
Gonad/foot	25	647	7.7	543
Muscular foot	15	379	0.7	196
Adductor muscles	41	1211	7.2	339
Whole animal	46	733	6.6	1681

Bivalve Molluscs

Scrobicularia plana, a deposit-feeding clam, is a characteristic species of intertidal estuarine muds and occurs around the margins of the middle region of the Creek, chiefly in muddy gravel deposits (Fig. 4). It is most common, however, in soft mud at the upper end of the Penpol area (R13) where densities of up to $40/m^2$ have been recorded (see below). Clams from the Creek often reach a large size (∿ 5 cm shell length) and a shell of 6.2 cm was found at Penpol.

Although concentrations of Cu and Zn in the Creek clams are abnormally high (Tables 13 & 14), they are not exceptional: similar or higher levels have been found in apparently less contaminated estuaries including other parts of the Fal System (Zn), the Gannel Estuary (Zn) and the West Looe Estuary (Cu). Among possible reasons for this anomaly are: (a) the availability of sediment Cu may be limited by binding to the high level of Fe oxide in the creek sediment (Luoma & Bryan, 1982); (b) the availability of sediment-bound Zn may be similarly limited or the animal may be approaching saturation with the metal; (c) the clam might avoid the worst of the conditions by not deposit-feeding, and suspension-feeding only when dissolved-metal levels are not too high. Further evidence for this last possibility is considered on p. 87.

Cerastoderma edule is widely distributed in the Fal Estuary System and is particularly abundant in the River Fal where densities of > 10 mm animals were $100\text{-}150/m^2$ at the Ardevora site (F7). Surveys of Restronguet

TABLE 14

SCROBICULARIA PLANA: CONCENTRATIONS IN CLAMS FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Six animals of about 4 cm length cleaned for 1 week prior to analysis

Highest concentrations underlined. For further details see Bryan *et al.* (1980)

Estuary	Site	Date	As	Cd	Cu	Fe	Mn	Pb	Zn
			µg/g dry wt						
			Restronguet Creek						
Restronguet Cr.	R6	Aug. 78	191	4.5	156	2700	17	50	3160
	R13	Mar. 79	190	2.3	89	2860	19	51	2580
	R16	Sept. 80	-	0.9	63	1195	17	20	2710
			Other parts of Fal system						
Tresillian Riv.	F1	Jan. 80	33	6.1	27	1460	12	40	3200
Calenick Cr.	F3	Apr. 80	-	8.9	79	1450	28	57	2920
Truro Riv.	F2	Dec. 74	-	8.3	55	2410	20	101	4190
Cowlands Cr.	F5	Apr. 80	-	1.2	25	770	33	31	1970
River Fal	F7	Apr. 80	-	2.1	27	2030	33	17	2790
Pill Cr.	F9	June 76	-	0.4	39	902	18	22	939
St Just Cr.	F14	May 80	-	0.93	63	469	16	21	1043
Mylor Cr.	F10	Mar. 80	-	2.7	49	892	17	52	3010
Mylor Cr.	F11	Mar. 80	-	1.2	44	847	14	43	2130
			Other contaminated estuaries						
Gannel	(upper)	Apr. 77	-	13.6	81	1910	261	991	4810
Tamar	(upper)	Feb. 80	-	3.3	39	2475	38	89	2181
West Looe	(upper)	Mar. 77	28	2.1	315	1310	70	489	2426
			Control estuaries						
Camel	(upper)	Jan. 80	27	0.4	19	989	18	8	309
Torridge	(lower)	Sept. 80	-	0.9	52	798	126	23	539

Creek failed to reveal any cockles living in the sediments, but in January 1980 13 animals of 7-14 mm were found on the surface near site R16. Eight of these cockles died whilst being kept in clean water prior to analysis, and the high level of Fe observed in the survivors (Table 15) suggests that they were moribund and had not purged themselves of sediment particles. Correction of the results by assuming that all the Fe reflects contamination from sediment particles, reduces the tissue concentration of Cu by almost

TABLE 15

CERASTODERMA EDULE: CONCENTRATIONS IN COCKLES FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Cockles cleaned for 2-3 days before analysis. Highest concentrations are underlined.

Estuary	Site	Date	No. cockles	Size (mm)	µg/g dry wt					
					Cd	Cu	Fe	Mn	Pb	Zn
					Restronguet Creek					
Restronguet Cr.	R15-17	Jan. 80	5	11	2.1	486	5029	87.6	21.0	1082
	R16	Apr. 81	1	35	3.0	174	1692	13.8	7.6	303
63d transplant ‡	R18	Nov. 80	6	26	0.87	141	1258	21.9	-	317
					Other parts of Fal System					
Carrick Rds *	(C8, 12, 15, 16, 17)	May 79	24	13	1.2	89	822	38.9	12.7	787
Mylor Cr.	F10	Mar. 80	5	36	1.4	91	1276	15.2	8.5	233
Mylor Cr.	F11	Mar. 80	1	47	1.3	59	1079	6.9	4.4	106
Pill Cr.	F9	June 76	1	39	0.38	12.8	431	2.1	2.8	87
Cowlands Cr.	F5	Apr. 80	2	38	0.64	8.0	1189	8.6	3.3	99
River Fal	F7	May 80	5	30	0.67	6.6	748	7.2	2.0	166
St Just Cr.	F14	May 80	4	37	0.52	7.8	760	4.3	2.1	79
Penrhyn Cr.	F13	July 76	5	34	0.52	4.7	328	3.3	6.5	92
Place Cove	F15	Mar. 79	1	41	0.40	5.0	572	3.2	2.5	79
					Other contaminated estuaries					
Tamar	(lower)	Mar. 80	6	34	2.7	7.3	1051	4.1	4.5	71
Gannel	(mid)	Mar. 76	4	30	3.5	11.6	1422	210	69.0	180
Par	(beach)	May 81	3	20	0.38	12.9	497	6.1	3.2	125
E. Looe	(mid)	Mar. 76	5	28	0.69	9.7	565	6.2	5.3	54
					Control estuaries					
Kingsbridge	(N. Quay)	June 74	5	36	0.45	6.0	305	3.0	4.3	40
Plym	(mid)	Mar. 80	5	33	0.67	3.7	412	1.6	1.8	38
Torridge ‡	(Appledore)	Sept. 80	6	28	0.43	4.2	431	18.8	0.4	46

*Parvicardium exiguum ‡Transplant Torridge → Restr. Cr.

TABLE 16

OSTREA EDULIS: CONCENTRATIONS IN OYSTERS FROM THE FAL ESTUARY SYSTEM COMPARED WITH VALUES FROM OTHER ESTUARIES

Animals cleaned for about 2 days before analysis. Highest values underlined

Estuary	Site	As	Cd	Cu	Fe	Mn	Pb	Zn	
		μg/g dry wt							
		Restronguet Creek							
Restronguet Cr	(R22-25)	19	-	1450	-	-	-	4150	Orton (1923)
		11	-	4000	-	-	-	5100	Orton (1923)
(extremely green)		-	-	16500	-	-	-	10500	Orton (1923)
(green oysters)		39	9.0	3874	157	8.1	-	14890	Sept. 1971
(pale oysters)		25	5.9	769	134	6.8	14	6004	Sept. 1971
(green oysters)		-	7.9	2614	219	16.7	2.5	17080	Feb. 1980
		-	-	1105	-	-	-	6290	George *et al.* (1978)
		17	3.0	2161	-	-	-	7167	Klumpp & Petersen (1979)
		Other parts of Fal system							
Carrick Rds	(C4,7)	-	3.9	957	386	15.9	2.8	4860	May 1979
	(C15,16,19)	-	3.5	912	294	13.0	2.4	5082	May 1979
	(C8,17)	-	3.6	609	246	8.8	2.2	3773	May 1979
St Just Pool		-	-	1450	-	-	-	3000	Orton (1923)
		Other areas							
Menai straits		-	5.2	392	223	17.9	6.2	3437	Boyden (1977)
Poole H.	(outer)	2.6*	5.9	86	394	7.0	8.0	1966	Boyden (1975)
Knysna	(S. Africa)	-	3.1	38	167	6.0	-	660	Watling & Watling (1976)

*Leatherland & Burton (1974)

50% and that of Zn by about 25%. Even so, these cockles, contained higher levels of Cu and Zn than were found in a single 35 mm, apparently-healthy cockle found on the surface in the same area in March 1981, or in cockles transplanted to the Creek for 63 d (Table 15).

Cockles from other parts of the Fal System also contain abnormally high concentrations of Cu and Zn: this is seen in samples from Mylor Creek and is also apparent in the small cockle *Parvicardium exiguum* collected from the Carrick Roads off the mouth of Restronguet Creek (Table 15).

TABLE 17

OSTREA EDULIS: TISSUE CONCENTRATIONS IN GREEN OYSTERS FROM RESTRONGUET CREEK (SEPT. 1971)

Tissue	% dry wt	µg/g dry wt (from 5 oysters)						
		As	Cd	Cu	Fe	Mn	Pb	Zn
Blood cells	11.3	-	2.7	23450	652	ND	6.2	61820
Blood plasma	4.1	-	2.4	305	63	2.1	7.5	1225
Muscle	26.1	38	8.3	1063	74	1.7	2.9	463
Mantle	23.1	-	11.8	6043	293	25.2	4.5	19750
Gills	20.2	66	8.9	6807	160	23.6	4.9	24250
Palps	29.3	-	10.2	4585	138	7.7	ND	15920

ND = not detectable

Ostrea edulis is common in the Fal Estuary System and there is a long-established oyster fishery: some oysters are grown at the seaward end of Restronguet Creek and are subsequently decontaminated by relaying elsewhere. Since at least the middle of the last century, it has been recognised that Fal oysters sometimes assume a green coloration through the accumulation of Cu but are otherwise apparently unaffected (O'Shaughnessy, 1866). Later, Orton (1923) showed that oysters from the Creek also contain high concentrations of Zn and to a lesser degree As. These observations are borne out by more recent analyses of oysters from the Creek and other localities (Tables 16 & 17). The bottom line of Table 16 shows that oysters grown in an uncontaminated South African estuary contained relatively low concentrations of Cu and Zn, although the spat originated in the United Kingdom.

The results for Creek oysters in Table 16 show great variability and reasons for this were examined by Boyden & Phillips (1981) who transplanted Pacific oysters, Crassostrea gigas, to the area and followed fluctuations in growth and metal content for 17 months in 1972-73. Mean concentrations of Cu and Zn ranged from around 7000 and 14000 µg/g respectively during the winter months to 2000 and 5000 µg/g in the summer. These fluctuations were attributed to various factors including the dilution of metals by tissue growth in the summer, metal losses through spawning, and seasonal changes in input (see Fig. 6).

TABLE 18

MYTILUS EDULIS: CONCENTRATIONS IN MUSSELS FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE FROM OTHER ESTUARIES

Animals cleaned for 2 days before analysis. Highest values underlined

Estuary	Site	Date	µg/g dry wt						
			As	Cd	Cu	Fe	Mn	Pb	Zn
			Restronguet Creek						
6 month transplant*	R10	Apr. 81	-	6.6	87	310	10.6	43	1548
5 month transplant‡		Oct. 74	-	1.6	~50	201	5.4	14	264
4 month transplant*	R25	Feb. 81	-	4.9	40	332	9.8	-	368
Restronguet Pt†	R23	-	17	1.0	15	-	-	-	167
			Other parts of Fal system						
Penryn Cr.	F13	July 76	-	2.2	7	274	4.7	85	323
			Other estuaries						
Tamar (transplant)*	(Saltash)	Oct. 80	-	2.4	7	186	11.6	21	145
Helford	(Bishop's Q.)	June 74	-	1.1	11	180	4.0	8	103
Plym	(upper)	June 74	-	23.2	13	175	22.0	37	330
Southampton Water**		-	11	2.5	-	-	-	-	269
Poole H.‡	(outer)	Feb. 74	-	3.7	7	91	-	-	97

*Transplanted from Tamar to Restronguet Cr.; ‡ Boyden (1977) transplant from Helford; †Klumpp & Petersen (1979); **Leatherland & Burton (1974)

Mytilus edulis is not very common in the Fal System and is extremely rare in Restronguet Creek. However, Klumpp & Petersen (1979) analysed some mussels from Restronguet Point (R23) and found relatively low concentrations of Cu and Zn (Table 18). On the other hand, much higher concentrations were found in mussels transplanted to the same general area for several months by Boyden (1977) and the authors (Table 18; see also p. 89). Animals from Penryn Creek also appear to be contaminated with Zn but the level of Cu is almost 'normal'.

Macoma balthica was collected from the relatively uncontaminated Ardevora site (F9) on the Fal Estuary. Results from these animals in Table 19 show no evidence of Cu contamination but levels of Zn are comparable with those

TABLE 19

MACOMA BALTHICA: CONCENTRATIONS IN CLAMS FROM FAL SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

About 10 animals of ∿15 mm length cleaned for 1 week prior to analysis

Estuary	Site	Date	µg/g dry wt					
			Cd	Cu	Fe	Mn	Pb	Zn
			Fal system					
Fal River	(F7)	May 80	0.38	47	869	12.1	3.8	693
			Other contaminated estuaries					
Tavy	(mid)	Aug. 81	1.24	105	650	29.8	24.5	691
E. Looe	(mid)	Mar. 76	-	338	788	24.4	60.6	1014
			Control estuaries					
Plym	(mid)	Jan. 80	0.96	74	626	9.1	9.1	559
Torridge	(Appledore)	May 80	-	50	1131	33	6.2	337

in animals from the Tavy Estuary which is moderately contaminated with metalliferous mining wastes.

Bivalves from the Carrick Roads

Table 20 gives results for *Venus striatula*, *Venerupis pullastra*, *Venerupis aurea* and *Chlamys varia* : concentrations in *Parvicardium exiguum* have already been given in Table 15. Animals were dredged from a number of different sites off the mouth of Restronguet Creek (Fig. 5) and were pooled for tissue analysis. Comparisons with the same or related species from uncontaminated areas indicate that those from the Carrick Roads are significantly contaminated with Cu and Zn.

Bivalve Summary

There is evidence that all nine species of bivalve collected in Restronguet Creek and the Carrick Roads are appreciably contaminated with both Cu and Zn. Oysters have a particular capacity for accumulating these metals and, occasionally Cu and Zn together account for about 2% of the dry tissue weight in animals from the mouth of the Creek. Cockles and

TABLE 20

CONCENTRATIONS IN BIVALVES FROM CARRICK ROADS (MAY 1979)

COMPARED WITH VALUES FROM UNCONTAMINATED LOCALITIES

Bivalves cleaned for 2-3 days and pooled from several sites

Locality	Sites	No. of animals	Length (cm)	µg/g dry wt					
				Cd	Cu	Fe	Mn	Pb	Zn
				Venerupis aurea					
Carrick Rds	(C8,10,12)	10	3.1	1.2	111	400	5.3	2.2	199
				Venerupis pullastra					
Carrick Rds	(C9,12,15,17)	5	3.8	2.5	25	966	8.0	4.9	81
S. Devon Coast	(Wembury)	5	1.6	0.5	3.0	62	3.0	2.7	25
				Venus striatula					
Carrick Rds	(C6,7,16,19,20)	8	2.1	1.1	51	725	7.7	10.4	177
Yealm	(Misery Pt)	3	2.6	1.1	19	660	6.6	32.0	68
				Chlamys varia					
Carrick Rds	(C10,18)	3	4.5	4.0	54.4	214	51.2	6.6	2069
				Chlamys varia tissues					
Digestive gland	(C4,10,15,17)	5	4.7	29.0	164	601	9.2	7.2	251
Kidneys		5		106	704	325	1363	190	76300
Adductor muscles	fast	5		0.6	2.8	65	3.5	1.7	153
	slow	5		1.0	3.4	95	4.1	1.1	141
Mantle		5		2.2	9.5	263	8.1	2.0	119
Gills		5		6.4	16.5	357	8.4	1.9	173
Gonad/foot		5		1.9	17.5	197	28.7	3.1	506
				Chlamys opercularis (Bryan 1973)					
Looe Bay		6-11	∿6.0	5.5	15.4	113	158	12.0	462

mussels are not usually found in the Creek, but concentrations of Cu and Zn in transplanted animals increased by approximately an order of magnitude. Curiously, *Scrobicularia plana*, the only fairly widely distributed bivalve in the Creek, does not accumulate such high concentrations of these metals as animals from several seemingly much less contaminated estuaries.

Gastropod molluscs

Littorina littorea and L. littoralis are found in the seaweed zone in the lower one-third of Restronguet Creek and contain levels of Cu, Zn and As exceeding those of winkles from any other British estuaries (Tables 21 & 22; see also Bryan, 1983; Bryan et al., 1983).

Nucella lapillus, the dogwhelk, occurs at Restronguet Point (R23) and accumulates higher concentrations of Cu and Zn than animals from other parts of the Fal System or other estuaries (Table 23).

Patella vulgata from outside Restronguet Point (R24) appear to contain lower concentrations of Cu and Zn than limpets from Mylor Harbour (F12) and also from the mouth of the Red River which drains tin mines in the Camborne area (Table 24).

Gastropods from the Carrick Roads

Table 25 includes results for four species dredged from various sites off the mouth of Restronguet Creek. Exceptionally high levels of Cu occur in Nassarius reticulatus and Ocenebra erinacea, and even under more normal conditions the former species contains a large amount of Cu. Some of this Cu almost certainly occurs as the blood respiratory pigment haemocyanin, but this is also true of gastropods such as L. littorea and N. lapillus which normally possess an order of magnitude less Cu than N. reticulatus (Tables 21 & 23). In the whelk Buccinum undatum from the Carrick Roads concentrations of both Cu and Zn are abnormally high, but in the slipper limpet Crepidula fornicata Zn, but not Cu, appears to be regulated.

Gastropod summary

All eight species of gastropod collected in the Fal Estuary System have enhanced levels of Cu, which in Littorina littorea, Nucella lapillus and Patella vulgata are about an order of magnitude higher than normal. Levels of Zn are similarly enhanced in L. littorea, L. littoralis and N. lapillus from the Creek, but in P. vulgata and species from the Carrick Roads smaller increases are observed.

TABLE 21

LITTORINA LITTOREA: CONCENTRATIONS IN WINKLES FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Winkles cleaned for 2-3 days before analysis.
Highest concentrations are underlined.

Estuary	Site	Date	µg/g dry wt As	Cd	Cu	Fe	Mn	Pb	Zn
			Restronguet Creek						
Restronguet Pt	R23	Mar. 78	70.5	2.8	1069	492	158	3.0	956
Pandora Inn	R22[†]		-	2.7	590	498	54	9.0	250
	R22	Feb. 72	-	1.6	554	581	99	0.3	233
Weir Pt	R25		-	1.3	261	275	64	0.9	197
			Other parts of Fal System						
Mylor H.	F12		-	1.3	464	268	49	-	179
Falmouth H.	F16		-	1.2	222	279	20	2.3	121
Falmouth B.	F17		-	1.0	93	243	10	0.3	91
			Other contaminated estuaries						
West Looe	(upper)	Mar. 76	35.9	2.6	161	458	133	70	83
Bristol Channel	(Clevedon)[‡]		-	210	-	-		3	520
Bristol Channel	(Penarth)*		-	-	249	-	60	15	186
			Control estuary						
Torridge	(Appledore)	May 80	19.0	2.0	129	399	42	2.2	75

[†] Boyden (1977) ; [‡] Butterworth *et al.* (1972); * Ireland & Wootton (1977); others Bryan *et al.* (1983)

TABLE 22

LITTORINA LITTORALIS: CONCENTRATIONS IN WINKLES FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER ESTUARIES

Winkles cleaned for 2-3 days before analysis.
Highest concentrations are underlined.

Estuary	Site	Date	µg/g dry wt As	Cd	Cu	Fe	Mn	Pb	Zn
			Restronguet Creek						
Pandora Inn	R22	June 76	-	5.6	841	332	233	9.3	1720
Restronguet Pt	R23*	-	98	-	-	-	-	-	-
			Other parts of Fal System						
Mylor Cr.	F11	Mar. 80	-	6.0	1183	378	98	4.7	847
Pill Cr.	F9	June 76	-	4.7	649	431	197	5.9	607
Cowlands Cr.	F5	Apr. 80	-	1.2	244	418	90	3.4	163
St Just Cr.	F14	May 80	-	1.6	220	472	57	3.8	167
			Other contaminated estuaries						
Severn	(Severn Beach)[‡]	-	12	178	-	-	-	-	312
Severn	(New Passage)	Oct. 76	-	171	131	311	54	4.9	296
Tamar	(Cargreen)	Feb. 78	-	15.7	726	314	188	16.7	176
			Control locality						
S. Devon Coast	(Wembury)	May 78	-	4.5	98	234	20	3.7	123

*Klumpp & Petersen (1979); [‡] Leatherland and Burton (1974).

TABLE 23

NUCELLA LAPILLUS: CONCENTRATIONS IN DOGWHELKS FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER AREAS

Animals cleaned for 2 days before analysis.
Highest concentrations are underlined.

Estuary	Site	Date	µg/g dry wt						
			As	Cd	Cu	Fe	Mn	Pb	Zn
			Restronguet Creek						
Restronguet Pt	R23	Mar. 79	-	23	1002	383	37	5.0	3352
	R23*		48	-	-	-	-	-	-
Weir Pt	R25	Feb. 72	-	13.6	433	334	18.8	3.9	1615
			Other parts of Fal System						
Mylor H.	F12		-	12.4	400	537	17.7	3.1	1956
Falmouth H.	F16		-	6.5	305	281	15.1	6.3	503
Falmouth B.	F17		-	13.1	177	327	13.8	1.5	822
			Other contaminated estuaries						
Red River	(mouth)	Mar. 72	-	4.7	809	185	12	1.0	323
Looe	(max.)‡		-	13.0	110	214	17	5.1	416
Bristol Channel	(Brean)†		-	425	-	-	-	27	3100
			Control areas						
Portland**			38	21	-	-	-	-	415
South Devon	(coast)		-	23	66	234	13	5.0	351

*Klumpp & Petersen (1979); ‡Bryan & Hummerstone (1977); †Butterworth *et al.* (1972); **Leatherland & Burton (1974).

TABLE 24

PATELLA VULGATA: CONCENTRATIONS IN LIMPETS FROM FAL ESTUARY SYSTEM COMPARED WITH THOSE IN OTHER AREAS

Animals cleaned for 2 days before analysis.
Highest concentrations are underlined.

Estuary	Site	Date	µg/g dry wt						
			As	Cd	Cu	Fe	Mn	Pb	Zn
			Restronguet Creek						
Restronguet Pt	R24*		37	16	45	-	-	-	243
			Fal Estuary System						
Mylor H.	F12	Jan. 72	-	12.9	90	669	11.4	8.8	326
Falmouth H.	F16	Jan. 72	-	5.4	46	1070	3.7	32.0	401
Falmouth B.	F17	Jan. 72	-	3.0	25	2660	24	10.2	225
			Other contaminated estuaries						
Red River	(mouth)	Mar. 72	-	24.0	147	750	15	19	323
Looe	(max.)‡		-	21.0	27	2330	36	38	224
Bristol Channel	(Portishead)†		-	717	37	2594	-	14	434
			Control areas						
Southampton Water**			13	2.7					
Portland**			24	8.1	-	-	-	-	95
South Devon	(coast)		-	12	10	973	6	9	107

*Klumpp & Petersen (1979); ‡Bryan & Hummerstone (1977); †Boyden (1977);
**Leatherland & Burton (1974).

TABLE 25

CONCENTRATIONS IN GASTROPODS FROM THE CARRICK ROADS

(MAY 1979) COMPARED WITH VALUES FROM OTHER AREAS

Animals cleaned for 2 days before analysis.
Samples pooled from several sites.

Species and site	µg/g dry wt					
	Cd	Cu	Fe	Mn	Pb	Zn
<u>Nassarius</u> <u>reticulatus</u>						
Carrick Rds (C12, 6)	1.6	7290	5350	26.8	7.4	1385
(C8, 10, 15)	2.0	4080	3210	31.1	10.7	906
Cawsand Bay	2.1	2600	655	73.0	5.6	617
Plymouth Sound	2.5	1160	506	66.0	6.5	811
<u>Ocenebra</u> <u>erinacea</u>						
Carrick Rds (C17)	23.8	3770	762	12.4	8.3	2850
<u>Buccinum</u> <u>undatum</u>						
Carrick Rds (C15, 16)	4.0	510	338	4.8	2.8	3020
Looe Bay*	6.5	123	65	6.0	9.1	508
<u>Crepidula</u> <u>fornicata</u>						
Carrick Rds (C7)	0.5	433	223	21.5	2.8	84
Poole Harbour*	11.5	198	-	22.6	11.4	82
Southampton Water[†]	1.4	-	-	-	-	116
S. Devon coast	1.1	132	376	130	2.3	111

*Boyden (1977); [†] Leatherland & Burton (1974)

<u>Crustaceans</u>

<u>Corophium</u> <u>volutator</u>, a burrowing amphipod, was found in the summer of 1971 at site R3 on the banks of the Carnon River slightly farther upstream than the upper limit of <u>Nereis</u> <u>diversicolor</u>. Bearing in mind the high concentrations of dissolved metals to which this site is exposed, the differences in body concentrations of Cu and Zn between the Creek animals and controls from the Avon Estuary are remarkably small (Table 26). This is consistent with the presence of mechanisms for the regulation of these metals, and a degree of regulation was observed by Icely & Nott

(1980) in Cu-contaminated animals from Dulas Bay in Anglesey (Table 26). Copper is stored as large granules in the hepatopancreatic caeca of the midgut and may be voided through the gut following the disintegration of the storage cells.

Carcinus maenas is common in the lower and middle reaches of Restronguet Creek where there is adequate cover. For the most part the population is composed of juveniles measuring less than 30 mm across the carapace, but in the summer some crabs twice this size are found at upstream sites. In crabs from site R10, concentrations of Cu are less than three times 'normal' and those of Zn are less than twice 'normal' (Table 26). As with C. volutator these relatively modest increases are consistent with the contention that both metal are fairly efficiently regulated (Bryan, 1968; 1971). With regard to As, Klumpp & Petersen found 62 µg/g in crabs from the middle reaches of the Creek and 22 µg/g near the mouth.

Fish

Platichthys flesus was collected from site R1 in the Kennall branch of the Creek: determinations of Cu, Zn and Fe in these flounders are compared with those for similar-sized fish from the uncontaminated Avon Estuary in Table 26. Apart from some enhancement of Cu in the liver, there is little evidence from the tissue levels that the Creek fish were exposed to metal contamination. They were netted from the River Kennall at low tide when the water was fresh and therefore relatively uncontaminated (see Table 1). However, the sediments in this area are highly contaminated with Cu and Zn and are inhabited by the most heavily Cu-contaminated Nereis diversicolor in Restronguet Creek (Table 10; R1), although levels of Zn in the worms are not exceptional. Thus the absence of very significant accumulation by the flounder suggests that either metals are not being absorbed from the diet or are being regulated in some way. Further studies on the accumulation of metals from contaminated N. diversicolor by fish were carried out using gurnards which will readily ingest whole worms.

When N. diversicolor from the flounder collection site (R1) were eaten by gurnards Trigla lucerna, there was similarly only slight evidence for the accumulation of Cu or Zn. Over a period of 22 days, fish of 20-30 g wet weight each consumed about 58 g wet weight of worms containing

TABLE 26

CONCENTRATIONS IN CRUSTACEANS AND FISH FROM RESTRONGUET CREEK COMPARED WITH THOSE FROM UNCONTAMINATED AREAS

Species and site		µg/g dry wt Cu	Fe	Zn
Corophium volulator				
Restronguet Cr (R3)		499	700	254
Dulas Bay, Anglesey*		259	325	109
Menai Straits*		77	494	104
Avon Estuary, Devon		113	732	149
Carcinus maenas (small ∿ 1g wet wt)				
Restronguet Cr. (R10)		527	-	282
Tamar (lower)		181	-	167
Carcinus maenas (large ∿ 50g wet wt)				
Restronguet Cr. (R10)		191	-	149
Tamar (lower)		77	-	77
Platichthys flesus (small 1.5 - 3.5g wet wt)				
Restronguet Cr. (R1)	liver	118	552	203
	viscera	28	302	123
	remainder	4.3	67	140
Avon Estuary (Devon)	liver	60	546	190
	viscera	12	265	114
	remainder	3.2	35	130

*Icely & Nott (1980)

about 300 µg/g of Cu on a wet weight basis or 2000 µg/g dry weight. If assimilated but not excreted, this level of input would increase the concentration of Cu in the fish by around 2000 µg/g dry weight of Cu. Table 27 compares concentrations of Cu in these fish after 22 days with levels in gurnards in which the input of Cu from uncontaminated worms was 60 times lower. Although levels of Cu and Zn are higher in the livers of fish having the high-Cu diet, this may in part be explained by the fact that their livers were relatively smaller and apparently in a

TABLE 27

TRIGLA LUCERNA: COMPARISON OF CONCENTRATIONS IN GURNARDS CONSUMING WORMS FROM RESTRONGUET CREEK OR CONTROL ESTUARIES

Fish wet wt at 22d (g)	Increase in wt at 22d (%)	Liver				Viscera		Remainder	
		Wet wt of organ as % total wt	% dry matter	µg/g dry wt Cu	Zn	µg/g dry wt Cu	Zn	µg/g dry wt Cu	Zn
		Diet of Restronguet Creek worms (high metal)							
19.4	-5.7	0.87	22.0	13.7	112	7.5	84	1.64	89
27.4	17.7	1.40	31.8	14.3	77	11.5	88	2.66	88
33.3	11.6	1.92	29.3	6.2	82	6.1	80	2.86	77
12.9	-	1.56	21.3	10.9	-	6.8	-	3.62	-
Mean	7.9 ±12.1	1.44 ±0.44	26.1 ±5.2	11.3 ±3.7	90 ±19	8.0 ±2.4	84 ±4	2.69 ±0.81	85 ±7
		Diet of Plym or Avon Estuary worms (low metal)							
13.7	14.6	3.00	39.2	1.9	39	7.4	82	2.40	109
43.8	23.1	2.65	42.3	3.8	57	5.0	86	1.48	60
21.7	-	2.69	31.7	6.1	-	6.0	-	1.02	-
Mean	18.8 ±6.0	2.78 ±0.19	37.7 ±5.4	3.9 ±2.1	48 ±13	6.1 ±1.2	84 ±3	1.63 ±0.70	85 ±35
		Comparison of mean values in t test (NS = not significant)							
P	NS	<0.01	<0.05	<0.05	<0.1	NS	NS	NS	NS

poorer condition than those in fish having a low-Cu diet (Table 27).

Faeces collected over the last 8 days of feeding contained levels of Cu 7.7 times higher than those of the ingested high-Cu worms. This suggests that much of the Cu (stored in phagolysosomes in the epidermal cells of *N. diversicolor*) passes through the gut of the fish without absorption: a lower faeces/worm ratio for Zn of 4.8 indicates that some Zn may be assimilated. Nöel-Lambot (1981) has shown that several species of teleost fish are able to limit metal uptake from the gut by the formation of intestinal mucous corpuscles having the capacity to bind heavy metals. Whether the production of such corpuscles by gurnards in response to the high-Cu diet is related to the apparently inferior liver condition of these fish remains to be seen. In addition it would be interesting to see if the livers of flounders from Restronguet Creek are in any way affected. Köhler & Hölzel (1980) observed liver deterioration in flounders from the Elbe Estuary in which the sediments are contaminated with a range of substances including high levels of Zn, Cd and Hg.

Summary

Although the crustaceans *Corophium volutator* and *Carcinus maenas*, and the flounder *Platichthys flesus* were collected in the more heavily contaminated parts of the Creek, their exposure to high concentrations of metals, particularly Cu and Zn, in waters, sediments and diet is belied by the relatively small increases observed in body concentrations. The main reason for this is the ability of these organisms to control concentrations of Cu and Zn in the tissues against environmental changes.

General summary

The concentrations of As, Cu and Zn in the environment and biota of Restronguet Creek are compared with values from uncontaminated localities in Table 24 : the contrast between these results is expressed as the ratio (Restronguet Cr./'Normal'). In all except two cases involving *F. vesiculosus*, ratios for the biota are far exceeded by those for the Carnon River input and the Creek sediments. The biota ratios are in part dependent on the site of collection and would be expected to decline downstream from area (1) to area (5). In addition, the ratios tend to reflect the abilities of various species to regulate metals. For example, high ratios for Cu in plants, and some species of polychaetes and bivalve molluscs reflect the accumulation and storage of Cu rather than its regulation. On the other hand, low Cu ratios for crabs *C. maenas* and fish *P. flesus* are indicative of regulation. By comparison with the water and sediment ratios for As, those for the biota are much lower, possibly reflecting some regulatory ability. The same is generally true of Zn, although some groups including plants and molluscs often having comparatively

TABLE 28

CONCENTRATION RATIOS COMPARING VALUES FROM RESTRONGUET CREEK AND VICINITY (RCr) WITH 'NORMAL' VALUES FROM BRITISH SITES (N)

Numbers in parentheses show approximate sample areas from head of Creek (1) to Carrick Roads (5)

	As			Cu			Zn		
	RCr	N	RCr/N	RCr	N	RCr/N	RCr	N	RCr/N
Fresh water (μg/litre)									
Carnon River (1)	233	2	116	689	1.8	383	12400	10	1240
Surface sediment (μg/g)									
Sediment (max.) (1)	2520	13	194	2540	19	134	3515	98	36
Plants (μg/g)									
Fucus vesiculosus (2)	184	15	12	1450	7	207	4220	99	42
Ascophyllum nodosum (3)	93	33	>2.8	546	8	68	1690	106	16
Salicornia sp. (roots) (1+2)	-	-	-	611	16	38	372	34	11
Coelenterate (μg/g)									
Actinia equina (3)	-	-	-	15	10	1.5	177	185	1.0
Polychaetes									
Nereis diversicolor (1)	87	7	12	1430	18	79	318	120	2.6
Perinereis cultrifera (4)	-	-	-	1210	12	101	489	130	3.8
Nephtys hombergi (2)	-	-	-	2227	36	62	518	252	2.1
Glycera convoluta (4)	-	-	-	828	42	20	483	169	2.9
Cirriformia tentaculata (4)	-	-	-	194	15	13	176	63	2.8
Tharyx marioni (4)	2335	1512	1.5	262	84	3.1	81	51	1.6
Melinna palmata (5)	-	-	-	3124	314	9.9	122	90	1.4
Bivalves (* = transplants)									
Scrobicularia plana (2)	191	27	7.1	156	19	8.2	3160	309	10
Cerastoderma edule (3)	-	-	-	486	3.7	131	1082	38	28
Ostrea edulis (4)	39	2.6	15	3870	86	45	17080	1966	8.7
Mytilus edulis (4+2)	17	11.4	1.5	87	7.1	12*	1548	97	16*
Venerupis pullastra (5)	-	-	-	25	3	8.3	81	25	3.2
Venus striatula (5)	-	-	-	51	19	2.7	177	68	2.6
Gastropods									
Littorina littorea (3)	70	19	3.7	1069	93	11	956	75	13
Littorina littoralis (3)	98	12	8.2	841	98	8.6	1720	123	14
Nucella lapillus (4)	48	38	1.3	1002	66	15	3352	323	10
Patella vulgata (5)	37	13	2.8	45	10	4.5	243	95	2.6
Nassarius reticulatus (5)	-	-	-	7291	1163	6.3	1385	617	2.2
Buccinum undatum (5)	-	-	-	510	46	11	3018	373	8.1
Crepidula fornicata (5)	-	-	-	433	132	3.3	84	82	1.0
Crustaceans									
Corophium volutator (1)	-	-	-	499	77	6.5	254	104	2.4
Carcinus maenas (large) (3+2)	62	<22	>2.8	191	77	2.5	149	77	1.9
Fisn									
Platichthys flesus (liver) (1)	-	-	-	118	60	2.0	203	190	1.1

high ratios are less efficient regulators than polychaetes, crustaceans and fish in which consistently low ratios are observed.

Although concentrations of Cd in the waters of Restronguet Creek are high, this is not reflected by levels in the biota. Since Cd is not usually regulated, it is thought that competition for uptake sites from the high ambient concentrations of Zn, and possibly other metals, suppresses the absorption of Cd.

Levels of dissolved Mn in the Creek are also high and in some species including macroalgae and littorinid gastropods concentrations are higher than 'normal'. On the other hand, concentrations in polychaete worms show only small variations and appear to be regulated; this is not really surprising, since worms are often exposed to high concentrations of Mn in the interstitial waters of uncontaminated sediments.

The abnormally high levels of Fe and Ag in the Creek sediments are usually reflected by higher levels in the biota. However, with Fe, it is often difficult to separate that which has been absorbed by the organism from that deposited at the body surface as the hydrated oxide. In the Creek this deposition may occur from the overlying water or, in burrowing species, from the high concentrations of dissolved Fe in the sediment interstitial water (see Table 6). Regulation of Fe is evident in some groups, for example nereid polychaetes, but it is necessary to clean the worms thoroughly in acid-washed sand prior to analysis in order to remove Fe from body surfaces.

Generally-speaking, concentrations of Pb in the Creek biota are not much higher than 'normal'. In a number of cases, the presence of additional Pb in the organism seems to reflect its association with a high level of Fe which, as stated above, may not actually have been absorbed.

Although the Creek sediments contain more than 1000 µg/g of Sn, concentrations in N. diversicolor only rarely exceed 1 µg/g. This is perhaps not unexpected, since most of the sediment Sn appears to occur as the very insoluble mineral cassiterite.

EFFECTS OF CARNON RIVER WATER AND RESTRONGUET CREEK SEDIMENTS ON ESTUARINE ORGANISMS

Toxicity of Carnon River water

Examples from the literature showing the relative toxicities of metals to bivalve embryos, crab larvae and non-tolerant adult ragworms are given in Table 29: for comparison, the average levels of these metals in Carnon River water are also shown. Concentrations of Cu and Zn in the River water exceed the lowest toxic levels by more than two orders of magnitude and, on this basis, these two metals are the most likely by far to exert environmental effects. In Restronguet Creek also, concentrations of Cu and Zn in the water (Fig. 7) regularly exceed the levels shown to be toxic to embryos and larvae (Table 29). Furthermore, the toxicities of metals in the Creek are likely to be additive and may also be enhanced by the stresses produced by the extremes of salinity and temperature typically encountered in tidal estuaries (MacInnes & Calabrese, 1978, 1979).

TABLE 29

COMPARISON BETWEEN CONCENTRATIONS IN WATER ENTERING CREEK AND TOXIC CONCENTRATIONS FROM LITERATURE

Lowest effective concentrations underlined

Metal	Concentrations in Carnon River water entering Restronguet Creek (Table 3) (µg/litre)	Lethal effects			Production of abnormal embryos	
		Oyster embryos* *Crassostrea virginica* ($25^{o}/_{oo}$; 26°C) 48 h LC50 (µg/litre)	Crab zoeae‡ *Cancer magister* ($34^{o}/_{oo}$; 15°C) 96 h LC50 (µg/litre)	Ragworm adults *Nereis diversicolor* ($17.5^{o}/_{oo}$; 13°C) 192 h LC50 (µg/litre)	Oyster embryos‡ *Crassostrea gigas* ($34^{o}/_{oo}$; 20°C) 48 h EC50 (µg/litre)	Mussel embryos‡ *Mytilus edulis* ($34^{o}/_{oo}$; 17°C) 48 h EC50 (µg/litre)
Cu	689	103	49	270	5.3	5.8
Ag	0.45	5.8	55	500	22	14
Zn	12400	310	456	30000	119	175
Pb	40	2450	575	>5000	758	476
Cd	25.6	3800	247	100000	611	1200
As	233	7500^{3}	232^{5}	$>25000^{3}$	326^{5}	$>3000^{5}$
Ni	135	1200	4360	130000	349	891
Mn	1792	16000	-	-	-	-

*Calabrese *et al*. (1973; 1977); ‡Martin *et al*. (1981) 3 = arsenite 5 = arsenate

Bivalve molluscs, particularly juveniles, appear to be among the most sensitive of estuarine organisms. The small-sized species Abra tenuis (Scrobiculariidae) has proved to be a convenient subject for use in toxicity experiments. Small individuals (2-3 mm) of this deposit-feeding bivalve from the Plym Estuary were used in groups of 30 to compare the toxicities of diluted Carnon River water with those of media containing different concentrations of Cu and Zn sulphates. Carnon River water diluted with filtered offshore sea water in the ratio of 1:3 killed 50% of the animals in 12 days, the end-point used being the failure of the shell to close when mechanically stimulated. The diluted River water contained 278 µg/l of Cu and 3000 µg/l of Zn. Comparable toxicity experiments with 75% sea water containing Cu and Zn sulphates in the ratio of 1:10 showed that 50% of the bivalves were killed in 12 days by somewhat lower concentrations (Table 30): on the other hand,higher concentrations were necessary when Cu and Zn were used singly.

TABLE 30

CONCENTRATIONS OF Cu AND Zn HAVING THE SAME TOXICITY TO ABRA TENUIS AS DILUTED CARNON RIVER WATER

Salinity 26.25°/oo; temperature 13°C; water changed regularly

12 day LC50 concentrations (µg/litre)

River/sea water ratio 1:3		Metals combined in 1:10 ratio		Metals used singly	
Cu	Zn	Cu	Zn	Cu	Zn
278	3000	250	2500	570	3750

The results show that Cu and Zn in the diluted River water are rather less toxic than in the experimental mixture: this is probably to be expected, since a fraction of the Cu in the River water medium was probably associated with particles of Fe oxide which had not settled out when the water was allowed to stand for 8 days before dilution. Even so, the Carnon River water exerts much of the toxicity expected from its composition : the effects of Cu and Zn (and possibly other metals) appear to be additive, since if Cu and Zn are used singly, the toxic concentrations are much higher (Table 30). In A. tenuis the threshold of Cu toxicity (used singly) appears to be around 100 μg/litre, whilst that of Zn is rather less than 1000 μg/litre. Experiments with similar-sized (2-3 mm) juvenile *Scrobicularia plana* from Cowlands Creek (site F5) indicated a comparable threshold for Zn but one of about 50 μg/litre for Cu. The 12 day LC50 concentrations were 325 μg/litre for Cu and 8000 μg/litre for Zn: i.e. lower for Cu but higher for Zn than in *A. tenuis*.

Toxicity of Restronguet Creek sediments

In addition to considering the toxicity of the water in Restronguet Creek it is necessary to establish the impact, if any, of the extremely metallic sediments. Before being used in experiments, surface sediments from different sites were sieved through 0.5 mm mesh and allowed to settle in seawater of 26.25°/oo salinity. Dishes containing different sediments were all placed in the same tank and completely covered with aerated seawater (26.25°/oo). Thus, in theory, all the dishes were exposed to dissolved metals leached from the sediments. Groups of small bivalves were introduced to the sediments and after 2-3 weeks the numbers of survivors were counted. The results of such an experiment are shown in Table 31. Sediments from Restronguet Creek are obviously toxic to both

TABLE 31

TOXICITY OF RESTRONGUET CREEK SEDIMENTS IN MARCH 1980 TO *ABRA TENUIS* AND *SCROBICULARIA PLANA*

Site of surface sediment	Survival (%) after 18 days at 13°C			Concentrations in surviving Tamar *S. plana* (μg/g)			
	A. tenuis (Plym) (30 of 1.6-3.2 mm)	*S. plana* (Mylor) (10 of 2.0-4.8 mm)	*S. plana* (Tamar) (5 of 9.6-12.8 mm)	No.	Cu	Fe	Zn
Restronguet Cr. (C7)	10	20	0	0	-	-	-
(C17)	7	50	40	2	440	3940	1590
(C15)	10	40	20	1	298	2653	1322
Mylor Cr. (F10)	100	100	100	5	260	3868	755
Original concentrations				6	154	1909	647

A. tenuis and S. plana, whereas the Mylor sediments, although fairly heavily contaminated (Table 4), are not. The overlying water contained about 40 µg/litre of Cu and 300 µg/litre of Zn leached from the sediments, but presumably all the animals were exposed to this. Analyses of Cu, Fe and Zn in the larger surviving S. plana indicate that concentrations had more than doubled in some animals during the 18 days of exposure. Based on these analyses it would seem unlikely that the uptake of Zn could be responsible for death, since comparable levels are sometimes found under field conditions. On the other hand, toxicity experiments involving the exposure of larger clams to dissolved Cu showed that a net increase of 150-200 µg/g in the tissue concentration was lethal: in Table 30 similar increases in the surviving clams suggest that Cu is the major toxic component in the surface sediments.

Additional experiments with Restronguet Creek sediments (site R7) have demonstrated their toxicity to other juvenile bivalves including cockles Cerastoderma edule and clams Macoma balthica.

Summary

Comparisons between metal concentrations in the Carnon River input and toxic levels from the literature lead to the conclusion that Cu and Zn are potentially the most toxic metals in Restronguet Creek. Experiments with the small bivalve Abra tenuis show that in the diluted river water the toxic effects exerted by Cu and Zn are additive, the lower toxicity of dissolved Zn being counteracted by its much higher concentration.

Under experimental conditions, sediments from the upper reaches of the Creek are lethal to small bivalves and Cu may be the most important toxic component.

The next section considers the composition of the biota in the Fal Estuary System as a whole in order to determine whether the fauna and flora of Restronguet Creek differs appreciably from that in other comparable tributaries of the System.

MARINE BIOTA OF THE FAL ESTUARY

The biological survey of the Fal Estuary system can be divided into three sections: (1) investigations of the macrofauna of the intertidal mudflats within the creeks of the tributaries of the Fal ('F' sampling sites - see Fig. 3); (2) the main survey of Restronguet Creek, including both rocky substrates (stations A-T - Fig. 12) and the mud and sand flats (see Fig. 15 for locations of traverses); and (3) a dredge survey of the benthic fauna inhabiting the northern part of the Carrick Roads ('C' sampling sites - Fig. 5). The major part of the survey focussed on the biota of Restronguet Creek, the other areas of the Fal system being investigated for comparative purposes in order to assess the extent and possible effects of metallic contamination. Most of the observations are based on qualitative samples. From the outset it was apparent that a full-scale quantitative survey of the Fal system would not be a practical proposition since the area involved is extensive and quantitative sampling would involve transporting large amounts of sediment over considerable distances of the mudflats which, in many parts, are difficult to negotiate and, further, preliminary observations had shown that quantitative samples would not yield sufficient data to justify the time and effort involved in their processing.

Intertidal macrofauna of the Fal mudflats

Excluding Restronguet Creek, the intertidal mud macrofauna was investigated in 1979-80 at 7 sites within the Fal system (see Fig. 4); these include the Truro River (F4), Cowlands (F5), Ardevora (F7), Philleigh (F8), Mylor (F10, F11), and St. Just (F14). For the most part, the areas sampled were between the levels of mid-tide and low water neaps; the fauna was assessed qualitatively by digging and hand-sorting the larger forms, the smaller-sized species being retrieved by washing through 0.25-1.00 mm meshes. Overall, the composition of the fauna inhabiting the mudflats proved to be fairly uniform and predictable throughout the estuary and therefore needs to be only briefly summarised.

As expected, Nereis diversicolor dominates the polychaete infauna, particularly above mid-tide level, but the small spionid Pygospio elegans is frequently also very numerous in small patches. Nephtys hombergi is generally common along with Melinna palmata and occasionally Ampharete acutifrons. Glycera convoluta tends to be widely scattered. Sieving of the surface layers reveals the presence of small-sized worms such as *Manayunkia aestuarina*, *Streblospio shrubsoli*, *Polydora* sp and the oligochaete *Peloscolex benedeni*: these species have patchy, strongly-aggregated distributions. Bivalve molluscs are chiefly *Scrobicularia plana* and *Cerastoderma edule*: at Ardevora (F7) these two species number about 400-500/m^2 and 100-150/m^2 respectively. *Macoma balthica* can usually be found but tends to be sparse and *Mya arenaria* is erratic in its occurrence. Bivalve juveniles are common in the surface layers; frequently sievings yield many *S. plana* juveniles below 4 mm in length, with fewer *C. edule* and some *M. balthica*. Sieved samples reveal very few *Abra tenuis* in the Fal (one taken at site F11, 3 at site F14); this is curious since *A. tenuis* is quite abundant in similar habitats elsewhere, such as in the Tamar and Plym estuaries (noted by Gibbs, 1982). Gastropod molluscs are the usual littorinids, *L. littorea* and *L. saxatilis*, plus *Hydrobia ulvae*, the latter occurring in typically dense clusters.

It can be concluded that the intertidal mud fauna of the Fal system is comparable to that found in other similar estuaries in southwest England such as the Tamar (see Spooner & Moore, 1940).

Biota of Restronguet Creek

Habitats

The substrates within Restronguet Creek may be conveniently divided into 'hard' and 'soft'. The hard substrates are chiefly found around the margins as low, mostly steep-sided, rock cliffs; exposed, mostly shaded, cliffs are fairly continuous along the south shore as far as opposite Devoran, extending down to MTL and beyond near the Creek mouth but only to about high water neaps in the upper reaches. Below the cliffs there is usually a band of loose rocks or shingle and this merges into the mudflat in a zone of muddy gravel. On the north shore, exposed rock cliffs extend only for a short distance inside the Creek (to about opposite transect B) and then banks of loose shingle and muddy gravel border the mudflats. The brown macroalgae and rocky shore fauna colonising the Creek margins were surveyed in April 1979 at selected sites along the south (stations A-H) and north (J-T) shores (see Figs. 12-14).

The 'soft' substrates composing the flats of the Creek can be broadly categorized as mud, muddy sand and coarse sand. Most of the

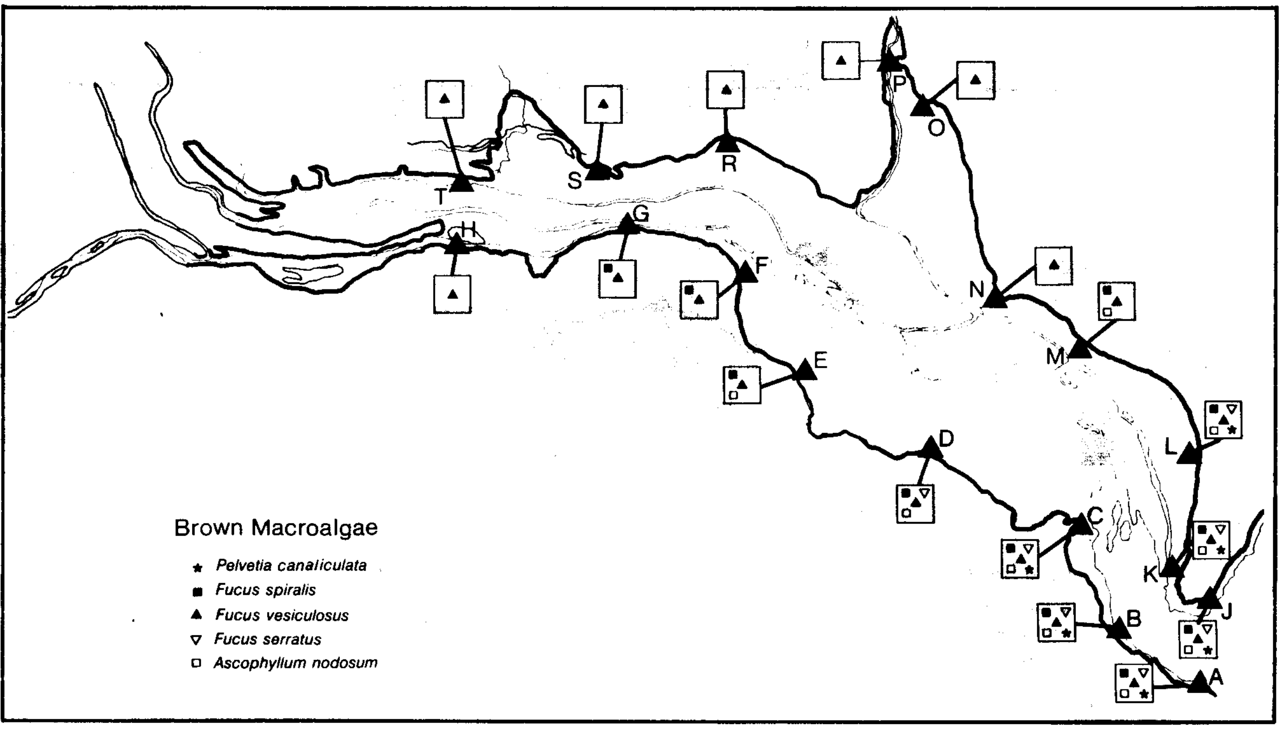

Fig. 12. Restronguet Creek: distribution of brown macroalgae.

area is covered by black mud, the consistency of which varies considerably; in some areas, particularly in the upper half of the estuary it is quite firm and easily traversed but in others, including most of the Penpol Creek, it is very soft and can be negotiated only with great difficulty and much effort. In contrast to these stable mudflats, at the mouth of the Creek there is a large area of clean, coarse sand that is maintained in a highly-rippled, mobile state by tidal currents. Between these two extremes, down the middle of the Creek, a narrow expanse of mixed deposit occurs as muddy sand; this sediment is far from uniform since digging often reveals a complex sequence of layered mud and sand, no doubt reflecting changes in river and tidal flow. The whole area of the Creek was surveyed in a semi-quantitative fashion by working transects of stations sited at intervals of 40-80 metres across the flats. At each station, areas of approximately 0.25 m^2 were dug out to a depth of 20 cm and the sediment sorted through by hand, noting each species present. Where possible, all individuals were counted but where a species was fairly numerous (> $20/m^2$), as at many of the N. diversicolor stations, it was noted as common. With this method it was possible to occupy 131 stations sited throughout the Creek (see Fig. 15) during one period of spring tides in April 1979.

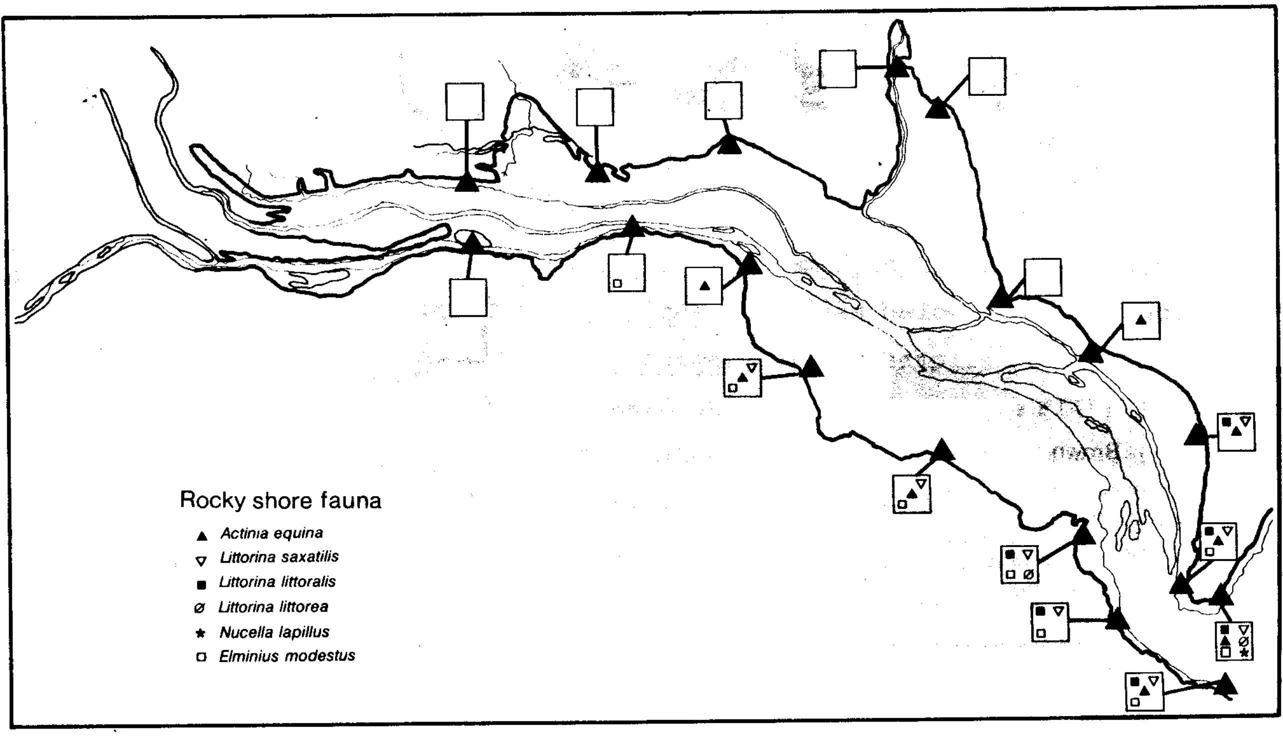

Fig. 13. Restronguet Creek: distribution of rocky shore species.

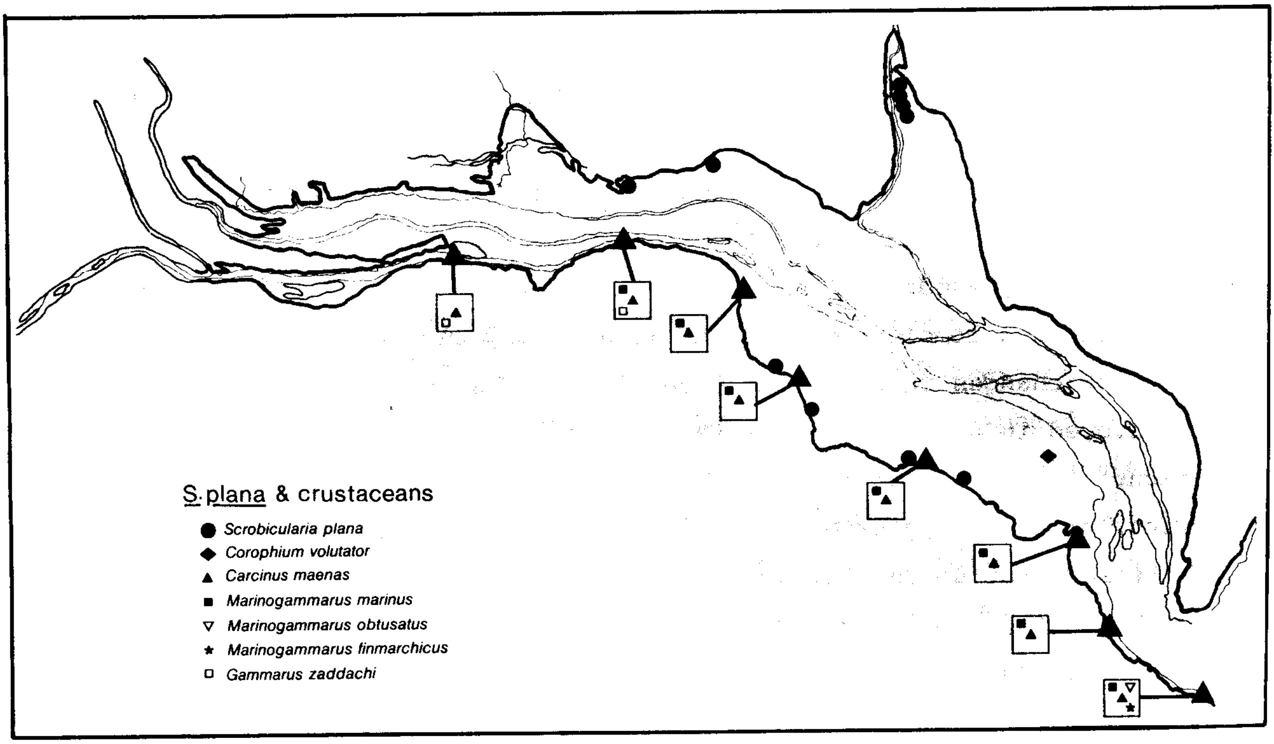

Fig. 14. Restronguet Creek: distribution of the bivalve Scrobicularia plana and crustacean species.

Rocky shore species

The distributions of the principal brown macroalgae within the Creek are illustrated in Fig. 12. All five of the common species - *Pelvetia canaliculata*, *Fucus spiralis*, *Fucus vesiculosus*, *Fucus serratus* and *Ascophyllum nodosum* - penetrate into the lower reaches and generally show the well-defined pattern of zonation typical of sheltered shores. On the north shore, four of the species die out rapidly leaving only *Fucus vesiculosus* colonising the shingle banks beyond Station M. On the south shore, however, the species less tolerant of estuarine conditions die out more gradually in the sequence *P. canaliculata*, *F. serratus*, *A. nodosum*, *F. spiralis*. *F. vesiculosus* continues upriver on both shores as far as Devoran where it becomes very patchy, and the plants stunted, before dying out altogether a short distance above stations H and T. The estuarine species *Fucus ceranoides* was looked for during the survey but was not recognised at any station; however, it may be present in the Creek.

The distributions of some animals associated with rocky habitats are summarised in Fig. 13. Three littorinid gastropods are to be found close to the mouth of the Creek - *Littorina saxatilis*, *Littorina littoralis* and *Littorina littorea* - but only *L. saxatilis* penetrates any distance, being found to about Station E. The dogwhelk *Nucella lapillus* does not appear to be present in the Creek although it occurs just outside. The anemone *Actinia equina* is widely distributed and particularly common under stones along the south shore, occurring up to Station E. Three barnacles, *Chthamalus stellatus*, *Balanus balanoides* and *Elminius modestus* occur on the upper-shore rocks inside the Creek entrance; the former two species die out rapidly but *E. modestus* continues to the confluence (St. G) where it survives in small numbers on rocks washed by river water. No *Mytilus edulis* has been found within the Creek.

Over much of the Creek's length there is a continuous population of gammarids which is composed of several species showing a typical succession. Samples were collected from beneath stones at about the level of high water neap tides along the south shore (Stations A-H). At the seaward end, three species occur - *Marinogammarus finmarchicus*, *Marinogammarus obtusatus* and *Marinogammarus marinus* (Fig. 14); the former two species are typically marine and do not appear to penetrate the Creek proper but *M. marinus* extends over much of the mid-estuarine region up to the confluence (St. G) where it overlaps in its distribution with the brackish-water species Gammarus zaddachi. The upper limit of G. zaddachi was not investigated.

Carcinus maenas is abundant everywhere in the Creek (Fig. 14) where there is adequate cover in the form of weed and rocks and also man-made debris (such as corrugated iron). For the most part the population is composed of juveniles measuring less than 30 mm across the carapace.

Mud and sand infauna

Nereis diversicolor is the dominant species over much of the area of the Creek (Fig. 15); in the upper half the extensive high tide mudflats support a dense population of this worm reaching 4000 individuals/m^2. The population extends along the banks of the tidal section of the River Kennall; the highest level at which N. diversicolor was found (Site 2) is about 1.4 metres above mean sea level, the level of mean high water neap tides; during some tidal cycles these worms would not be immersed for several days. Over the lower half of the Creek N. diversicolor is less abundant and more limited in its extent,presumably by a combination of tidal level and salinity regime but also the coarser grade and mobility of the sediment in the middle area of the estuary. Over large areas of the lower flats the population was found to be relatively sparse (less than 20/m^2) and at many stations only burrows were noted. These empty burrows appeared to have been recently occupied since the sediment lining was in many cases lighter in colour and evidently still oxidised. After spawning, N. diversicolor dies; spent individuals were seen in some numbers on the mud surface in April and hence it is thought that the uninhabited burrows were those of recently-spawned worms. Juvenile N. diversicolor (1-2 mm long) have been detected in the surface layers in both July and October and thus, whilst the main spawning of the Creek population may take place in spring, smaller spawnings probably occur during the summer months.

Nephtys hombergi and Nephtys cirrosa both occur in the Creek, the former is predominantly found in mud and muddy sand, the latter in clean coarse sand (see Clark & Haderlie, 1960). N. hombergi is probably the second most abundant polychaete in the Creek after N. diversicolor and is widely distributed over the lower half extending almost to Tallacks Creek (Fig. 16). In the survey the vast majority of specimens were small-sized (less than 30 mm long) and attained densities estimated at

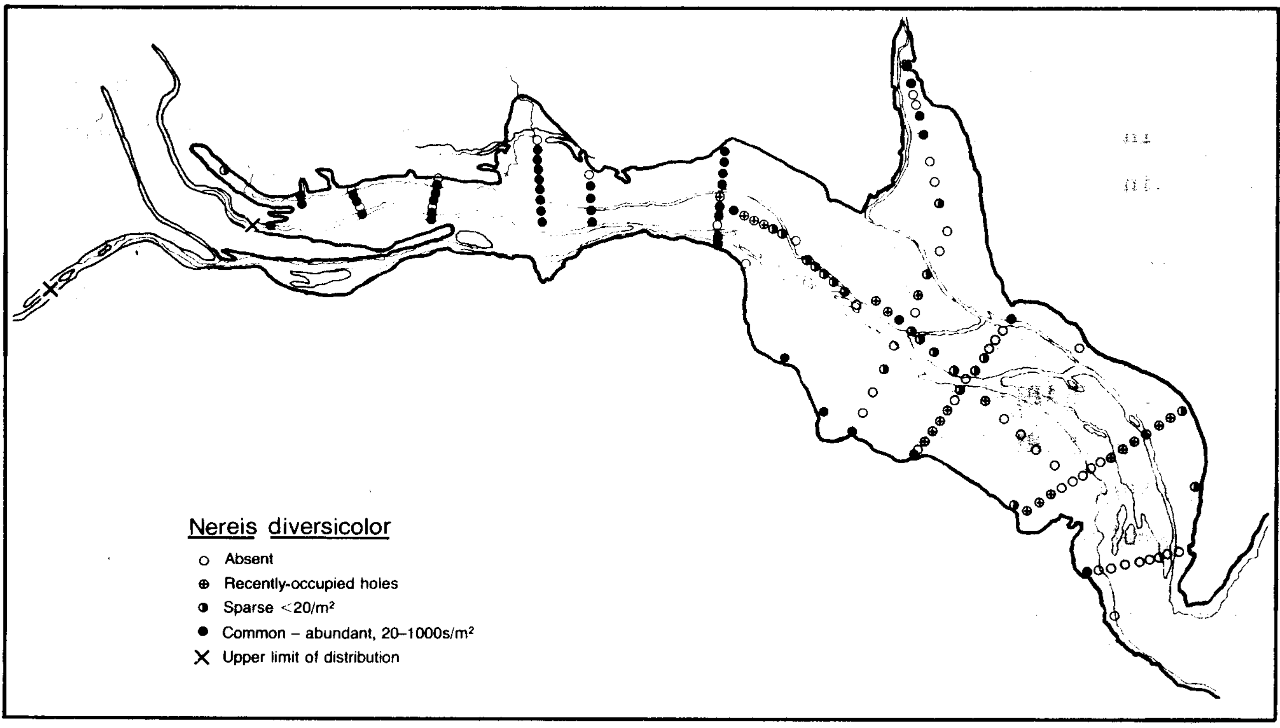

Fig. 15. Restronguet Creek: positions of survey transects and distribution of Nereis diversicolor.

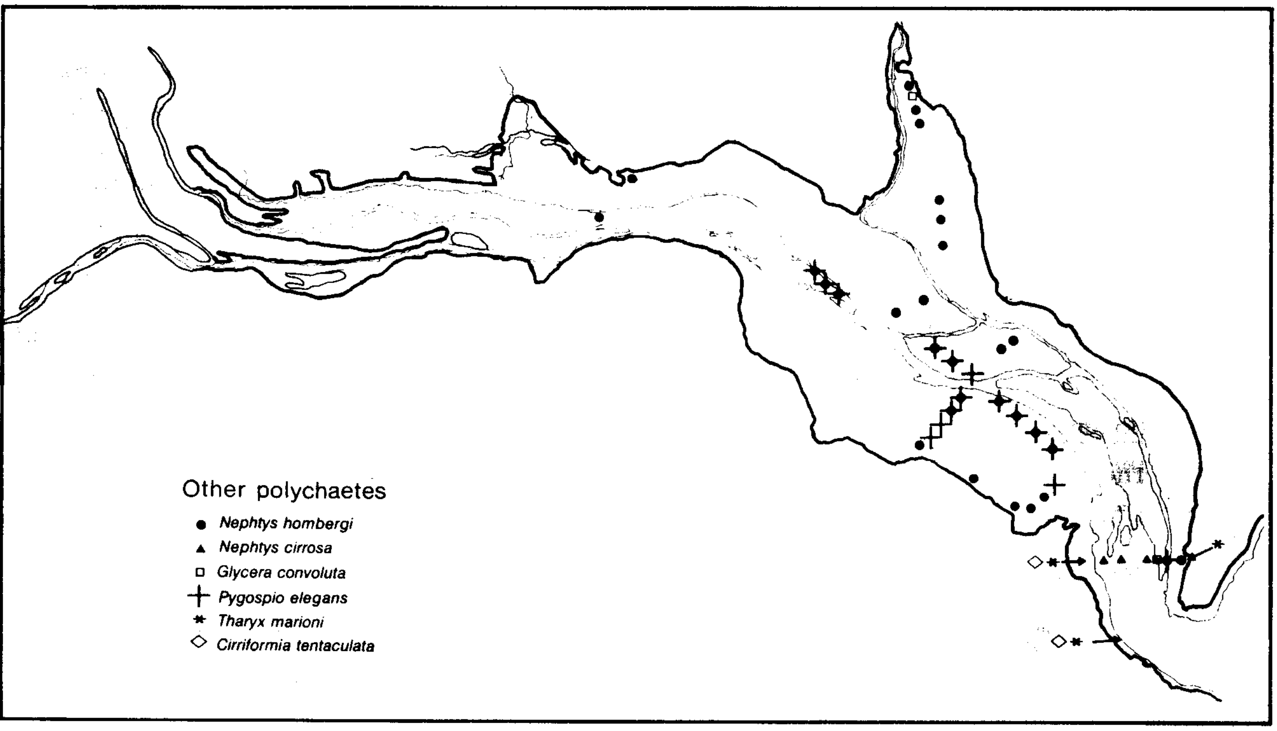

Fig. 16. Restronguet Creek: distribution of polychaete species other than N. diversicolor.

$30\text{-}50/m^2$. From casual observations over several years it would appear that the abundance of this species in any particular area of the Creek is liable to fluctuate quite markedly, possibly because of localised population movements. Juveniles (0.6-1.0 mm in length) have been found in surface samples taken in October 1979. *N. cirrosa* was found only in the coarse sands at the tide-swept mouth of the Creek.

Glycera convoluta is uncommon in the Creek: in the survey two specimens of this species were recorded, one in Penpol and one at the Creek mouth. On an earlier occasion (15 Mar. 79), seven specimens were found in fine gravel at Restronguet Point. Because of its rarity, little can be said concerning the distribution of *G. convoluta* but it would seem that a breeding population of this essentially-marine species is not established in the Creek.

Pygospio elegans is found in the centre of the lower half of the Creek predominantly in the mixed mud and sand deposits (Fig. 16). Its sandy tubes are fairly conspicuous despite their small size, but in the survey were never found in any abundance. Examination of the tubes showed that in July some females were brooding eggs or larvae (up to about 1 mm in length) and evidently the population is an established one, not one maintained by larvae carried into the Creek by the incoming tide. Recently-settled juveniles have been found in surface samples taken in summer as far upstream as Tallacks Creek; thus the juveniles of the *P. elegans* appear to be widely distributed within the Creek by tidal currents.

Several other polychaetes occur in the muddy gravel along the shoreline at the mouth of the Creek in the vicinity of Pandora but do not penetrate the estuary to any extent. These include two cirratulids, *Cirriformia tentaculata* and *Tharyx marioni*, a nereid, *Perinereis cultrifera*, (all of which extend into the sublittoral off the Creek) and a capitellid, *Notomastus* sp.; the latter two species were not taken in the survey. The oligochaete *Peloscolex benedeni* also occurs in the Creek chiefly where there is any quantity of decaying organic material. Large numbers have been recorded in the vicinity of Tallacks Creek.

Corophium volutator is often present in high numbers in estuaries but proved to be very rare during the survey, only one specimen being taken in the lower half (Fig. 14). However, in previous years the species has been seen in moderate numbers burrowing in the stiff mud along the banks of the Carnon River upstream from Devoran (Site R3); the reason for its scarcity in April 1979 is unknown.

Scrobicularia plana is seemingly the only bivalve penetrating the Creek to any extent. It is predominantly found around the margins of the middle Creek region, chiefly in muddy gravel deposits, but appears to be most common in the soft mud at the upper end of Penpol Creek: here densities of up to $40/m^2$ have been recorded. The reason for S. plana being limited to the margins of the mudflats is not understood: large areas of the mudflats in the middle Creek region appear suitable for its colonization. Elsewhere in the Fal and in other estuaries, such as the Tamar, it occurs from the level of mean high-water to that of low-water springs although concentrated in the upper half of the tidal zone to below mid-tide level (Spooner & Moore, 1940). It is interesting to compare the size-frequency distribution of the S. plana population at Penpol with that of the population at Ardevora (Site F7) (a bay that is roughly comparable in situation and area). The Penpol population is composed solely of large individuals between 30 and 55 mm in length (Fig. 17) and to judge from the winter shell-growth-checks these animals are all fairly aged, probably 8-12 years old. However, in the Ardevora population large individuals are seemingly rare or absent but all size-groups up to 35 mm in length are represented. A number of reasons can be forwarded to explain these differences but in the present context the point of interest is that the Ardevora population appears to have a fairly-regular annual recruitment whereas at Penpol no spat settlement would seem to have taken place for a number of years. Penpol individuals do appear to spawn: all specimens in a sample of 40 collected in July 1980 had ripe gonads filled with seemingly-mature gametes. Nevertheless, no spat or small juvenile of S. plana has ever been found in a surface mud sample taken in this area or in any other part of the Creek. These features suggest that spat settlement within the Creek is a very spasmodic event.

Cerastoderma edule was not found in the Creek during the main survey. However, in January 1980 some small individuals (7-14 mm long) were found scattered over the mud surface in the vicinity of transect B. All were lying exposed and did not appear to be thriving. Whilst it is possible these specimens represent the spat of 1979 it seems more likely that they had been transported from the outside grounds during rough weather. Two months later no live cockles were found in the area. No C. edule spat or juveniles have been found in surface mud samples from the Creek: it is

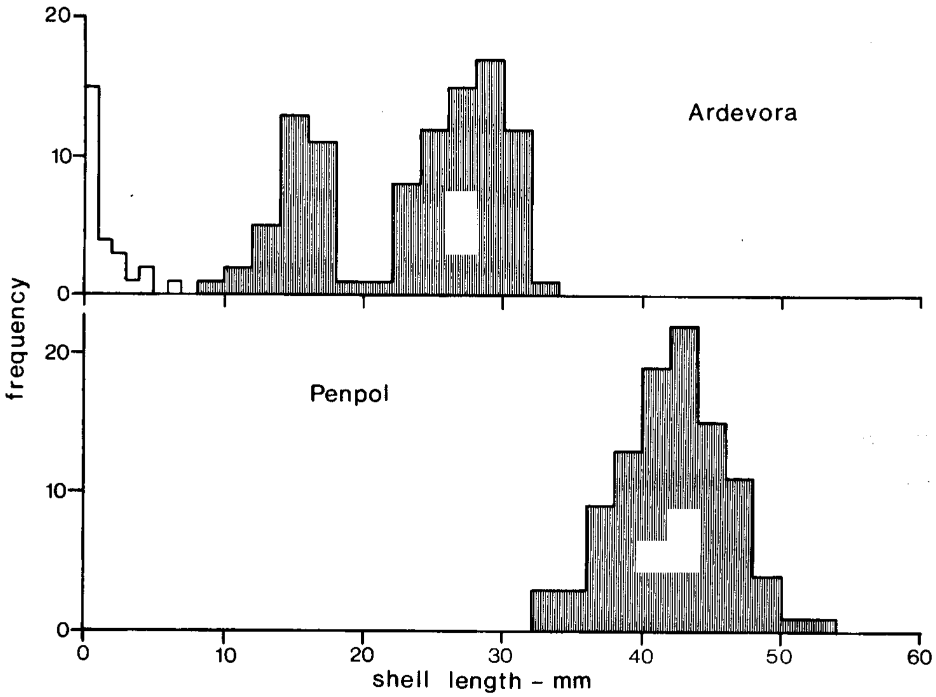

Fig. 17. Scrobicularia plana: comparison of size frequency distribution of populations in October 1979 at Ardevora (site F7) and Penpol (site R13). Open bars - juveniles from 250 μm sieved sediment sample (none taken at Penpol); hatched bars - adults hand-sorted from dug sediments.

therefore improbable the Creek supports a permanent population, unlike other similar inlets of the Fal.

Benthic Survey of the Carrick Roads

From the biological viewpoint the Fal Estuary is of great interest by virtue of the fact that it is one of the few areas around Britain that supports an oyster fishery based on natural stocks. The fishery has been studied for many years, notably by Orton in the 1920's (Orton, 1923, 1926, 1927, 1940) and more recently by Waugh (1972) and Walne & Wood (1973). However, apart from casual observations, little has been published on the general fauna of the estuary.

The present survey was undertaken to assess the benthic fauna of the northern part of the Carrick Roads between Pill and Mylor Creeks in the area adjacent to the mouth of Restronguet Creek. The survey was carried out 1-2 May 1979 and a total of 20 stations were sampled with a small rectangular naturalist's dredge. This type of dredge effectively samples the surface and shallow-burrowing fauna to a depth of 5-10 cm depending on the hardness of the ground; deep-burrowing forms may be missed. For this survey the dredge was fitted with a fine stramin net to prevent washing-out of the sample during hauling. At each station a part of the sample (about 10 litres of sediment) was washed through a sieve mesh of 1.0 or 2.0 mm diameter, the size depending on the deposit type, and the material retained on the sieve preserved with formalin to be sorted later in the Laboratory under a binocular microscope. The remainder of the dredge sample (10-30 litres of sediment) was washed through a 4.0 mm mesh and the larger animals picked out on board. The position, depths and sediment types of the sampling sites (Stations C1-C11 on the west side, C12-C17 on the East Bank and C18-C20 in the main channel) are indicated on Fig. 5 and in Table 32.

Within the area surveyed, much of the bottom is flat and at shallow depths between 0.5-2.0 metres. These shoal areas are known locally as 'Parson's Bank' and 'Mylor Bank' on the western side, separated from the 'East Bank' by the steep-sided main channel which extends to depths of 12-20 m (Fig. 5). Over the whole area the bottom is composed of mud and muddy sand with varying admixtures of coarser material in the form of fine to coarse shell gravel, lithothamnion (calcareous alga) fragments and stones (see Table 32). Off the mouth of Restronguet Creek the mud is rather stiff whereas in the main channel it is soft and fluid. The widespread abundance of shell gravel, consisting of broken and complete bivalve shells (chiefly Venerupis, Chlamys and Ostrea), no doubt reflects to some extent the efforts of generations of oyster fishermen to encourage oyster spat settlement by laying large quantities of clean shell on the bottom to act as 'cultch'.

The commoner species and their relative abundance in the samples are listed in Table 32. Rarer species are listed in Table 33.

Over the whole survey area, including the main channel the infauna is dominated numerically by polychaete worms notably Melinna palmata, Nephtys hombergi and Caulleriella spp. (chiefly Caulleriella caputesocis). Bivalves were taken in small numbers only, Abra alba being the commonest and most widespread. Venerupis pullastra, Venerupis aurea and Parvicardium exiguum all proved to be widely scattered but predominantly found in the mixed shell-gravel deposits on the East Bank.

TABLE 32

THE DISTRIBUTION AND RELATIVE ABUNDANCE OF THE COMMONER SPECIES TAKEN IN THE SURVEY OF THE CENTRAL PART OF THE FAL ESTUARY

See Fig. 5 for sampling sites. Scale of abundance: + = 1-5 individuals; ++ = 6-20; +++ = >20.

'C' STATION NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SEDIMENT	Stiff mud with stones	Stiff mud with stones and fine shell gravel	Stiff mud with stones and fine shell gravel	Muddy shell gravel with stones	Muddy shell gravel with stones	Muddy shell gravel	Muddy shell gravel	Stiff mud with shells	Muddy shell gravel	Stiff mud with stones, shells and lithothamnion	Muddy shell gravel	Muddy shell gravel with lithothamnion	Muddy shell gravel	Muddy shell gravel	Muddy shell gravel with stones/lithothamnion	Mud with shells and lithothamnion	Muddy shell gravel with lithothamnion	Soft mud	Soft mud	Soft mud
DEPTH (m)	1.0	0.9	0.5	1.0	0.8	0.9	7.5	0.2	0.7	1.0	1.0	1.0	1.8	0.8	0.2	2.0	0.9	22	25	19
SPECIES																				
Coelenterate																				
Sagartiogeton undata		+			+	+							+					+	+	
Annelida																				
Eulalia spp.				+				+		+	+				+				+	
Perinereis cultrifera	+										++				+		+			
Nephtys hombergi	++	++	++	+	++	++	+	+	+	+			+	+				++	++	++
Glycera convoluta	+										+	+		+	+		+			
Scoloplos armiger						+			+			+	+							
Polydora spp.					+	+	+		+					+						
Prionospio malmgreni							+				+			+			+			
Cirriformia tentaculata	++	+	++	+				++						+	+					
Caulleriella spp.			+	+++	+	+	+		+		+	+	+		+		+	+++	+++	+++
Tharyx marioni	+++	+	+						+	+										
Capitellidae spp.				+													+	+	+	+
Melinna palmata	+		+	+++	++	+++	+	+	+	+	+	++	+++	+		+	+	+++	+++	+++
Peloscolex benedeni								+		+	+				++			+		
Phoronida																				
Phoronis psammophila												++		+	+		+		+	
Mollusca																				
Nassarius reticulatus		+				+			+		+	+		+	+					
Akera bullata						+			+					+		+	+			
Ostrea edulis	+			+			++						+	+	++	+	+			
Chlamys varia				+								+			+		+	+		
Parvicardium exiguum		+						+	+		++	+		+	+	+	++			
Venus striatula						+	+									+		+	+	+
Venerupis aurea											+	+		++		+				
Venerupis pullastra (juv.)				+			+				++	+		+	+	+				
" " (ad.)											+		+		+		+			
Abra alba			+	+		+	+		+			+	+	+		+	+	++	+	++
Abra nitida	+			+	+	+				+			+					++		
Crustacea																				
Amphipoda spp.	+	+					+	+					+	+	+	+	+			
Pagurus bernhardus		+									+	+			+					
Carcinus maenas		+	+				+						+		+					
Macropipus arcuatus		+				+	+			+	+	+	+	++	++					
Macropipus depurator							+						+	+	+					

The juveniles of V. pullastra, 3-6 mm in length and probably representing the 1978 brood, were fairly common and more widespread than the adults. A few species were taken in high numbers in restricted areas, for example, the polychaetes Cirriformia tentaculata and Tharyx marioni, both of which are abundant in the stiff mud off Restronguet Creek (and extend into the intertidal zone at the Creek mouth).

Since the dredge was not towed for any distance, the surface-dwelling forms, such as oysters and the gastropod Nassarius reticulatus, were not taken in large numbers. All three crab species captured appeared to be most common on the East Bank, especially Macropipus arcuatus. The epifauna attached to shells and stones was not studied in detail but the tube-worms Pomatoceros triqueter and Serpula

TABLE 33

DREDGE SURVEY OF CARRICK ROADS : RARER SPECIES NOT INCLUDED IN TABLE 32

Species	Stations	Species	Stations
Coelenterate		Echiura	
Edwardsia callimorpha	18 19	*Thalassema thalassemum*	7
Nemertea		Mollusca	
Nemertea spp.	4 19	*Crepidula fornicata*	7 14
		Ocenebra erinacea	17
Polychaeta		*Buccinum undatum*	15 16
Aphrodita aculeata	19	*Philine aperta*	18
Pholoe minuta	11 15 17	*Anomia ephippium*	7
Sthenelais boa	4 14	*Thyasira flexuosa*	20
Phyllodoce spp	3 5 11	*Mysella bidentata*	14
Ophiodromus flexuosus	11		
Syllidia armata	11 14 17	Crustacea	
Exogoninae sp.	15	*Janira maculosa*	15
Platynereis dumerilii	11	*Crangon crangon*	4 15
Magelona alleni	9 19		
Maldanidae sp	4 14 19		
Myriochele sp.	5 19 20		
Megalomma vesiculosum	14 15		
Myxicola infundibulum	14		
Serpula vermicularis	7		
Pomatoceros triqueter	7		

vermicularis were commonly seen on the shells of *Chlamys varia*. Of the common pests of oyster beds, several clusters of the slipper-limpet *Crepidula fornicata*, a few green crabs (*Carcinus maenas*) and one specimen of the tingle-whelk *Ocenebra erinacea* were noted. No starfish (*Asterias rubens*) was found.

In the survey samples about 70 species are represented. The great majority of these are widely distributed forms that are common in the Channel (see Marine Biological Association, 1957; Holme, 1961, 1966) and elsewhere. In terms of species composition the fauna of Fal Estuary can be compared to that of Plymouth Sound where, in suitable deposits, all of the Fal polychaetes, with one exception, can be found (see Gibbs, 1969). (The exception is *Prionospio malmgreni* which has not been recorded around South-West England.) The number of bivalves taken in the central Fal is lower than expected and it is possible that several deep-burrowing forms, such as *Mya arenaria*, were missed by the dredge but no dead shells of these species were found. However, three bivalve species can be added to the survey list: Cerastoderma edule, Laevicardium norvegicum and Kellia suborbicularis, all of which were found by Waugh (1972) on Parson's Bank in 1961-62 but were not taken in 1979.

One interesting feature of the sediments is the large quantities of Bittium shells present in certain areas (Stations 9, 11, 12 and 17). No live specimens of this gastropod were discovered; in view of the abundance of these shells it must be assumed that either this snail was once common in the estuary or the shells were introduced along with the cultch for the oyster spat.

Discussion

Although more observations on the seasonal changes are required the present survey of the Creek has revealed several features of interest concerning the fauna of the intertidal flats.

Firstly, the bivalve fauna is very sparse both in numbers and variety. Only Scrobicularia plana occurs in any numbers and these are limited to the margins of the flats; in fact, in no area does this species appear to survive closer to the Carnon River than about 150 metres distance. It is perhaps surprising that Cerastoderma edule has no 'resident' population within the Creek; this species, which tolerates salinities down to $20^{o}/oo$ (Tebble, 1966) is present in quantity on suitable grounds within the neighbourhood, and certainly the muddy sand areas of the lower half of the Creek appear to be suitable grounds for this species. The absence of Macoma balthica from the Creek (but found elsewhere in the Fal) is noteworthy but perhaps not significant: in South-West England this species is rarely abundant and tends to be rather patchy in its distribution between and within estuaries. Venerupis shells are abundant over the lower half of the Creek but it is suspected these may have been imported as 'cultch' for oyster spat settlement.

Secondly, no specimens of Hydrobia ulvae have been noted in the Creek; this small gastropod commonly occurs in high numbers in estuaries, where it forms an important food source for birds such as the Shelduck, and this is presumably the case at other localities within the Fal Estuary system.

Lastly, few polychaete species inhabit the muddy sand of the lower Creek: apart from Pygospio elegans and Nephtys hombergi, both of which are common, several other estuarine species could be expected, particularly *Melinna palmata*, and also perhaps the cirratulid *Caulleriella caput-esocis*, which is common in the Fal Estuary benthos.

In seeking the explanation for the absence of typical estuarine mud species in the Creek and the restricted distribution of *Scrobicularia plana*, some of the conditions imposed by the metal contamination need to be considered. Any organism settling on the sediment surface must be able to tolerate wide fluctuations in salinity and high concentrations of certain metals, particularly copper and zinc. For the spat of bivalves, such as *S. plana*, *C. edule* and possibly also *Macoma balthica*, these conditions are almost certainly lethal over long periods, depending also on the inflow from the Carnon River (see p. 15). However, *Scrobicularia plana* larvae do survive but, to judge from the distribution of adults, only do so at the higher levels of the flats, i.e. around the margins; it seems possible that at these higher levels the length of time during which the recently-settled spat are exposed to high metal concentrations is minimal whereas lower down the shore the metal concentrations and exposure times are lethal.

The toxicity of the Carnon River water may also explain the absence of *Hydrobia ulvae* in Restronguet Creek. As demonstrated by the data shown in Fig. 9, the surface water of the incoming tide contains the highest metal concentrations and it is in this water that the *Hydrobia* would have to float whilst feeding on material trapped by their mucus rafts. The evidence suggests that *Hydrobia* is unable to tolerate or adapt to such high metal levels.

Although the polychaete fauna of Restronguet Creek is rather poor in species, the widespread distribution of the spionid *Pygospio elegans* is an interesting feature. The species is known to tolerate estuarine conditions down to 12-14^{o}/oo (Rasmussen, 1973). It has a rather complex breeding biology but briefly the eggs are laid in capsules within the burrow of the female and brooded so that the larvae are released at an advanced state of development. In the Creek these larvae appear to be widely distributed by tidal currents and have been found as far upstream as Tallack's Creek. During dispersal, these young stages, only 0.5-1.0 mm in length, must be subjected to widely fluctuating conditions of salinity and to relatively-high metal concentrations. Their tolerance of copper and zinc must be high and it is likely that the *P. elegans* population in the Creek has adapted to the metal contamination in much the same way as the population of N. diversicolor (see below).

Whether or not the heavy-metal discharge from Restronguet Creek affects the distribution of benthic animals in the Carrick Roads remains to be investigated in detail but from the results of the present survey it would appear that the effect is minimal in that most of the species recorded in the survey area were found within the vicinity of the Creek mouth. The East Bank appears to be more productive than the west side but this may be simply a reflection of the sediment types.

HEAVY-METAL TOLERANCE IN ESTUARINE SPECIES

Tolerance in Restronguet Creek Species

Based on a comparison between concentrations of Cu and Zn in the waters of Restronguet Creek and levels observed to be toxic under experimental conditions, several species are much more widely distributed within the Creek than might be predicted.

Fucus vesiculosus

The influence of exposure to dissolved Cu and Zn for 13 days on the growth of small (3-4 cm) plants from Restronguet Creek and the Tamar Estuary is shown in Figure 18. Although the Creek weed is slightly affected by the addition of 100 µg/litre of Cu, only 25 µg/litre has a considerable effect on the Tamar weed. During a period of 12 days following exposure, the Creek weed regained its original growth rate at all concentrations : however, recovery of the Tamar plants was less complete and those exposed to 250 µg/litre of Cu were dead. It was suggested by Bryan (1980) that tolerant weed is probably less permeable to Cu and that this, coupled with growth dilution, helps to limit the internal concentration and thus allows detoxication mechanisms more time to become effective. Tolerance to Cu may have a genetic basis since this has been observed in other seaweeds (Russell & Morris, 1970).

There is no evidence from the data shown in Figure 18 that the Restronguet Creek weed is especially tolerant to Zn, and 1000 µg/litre had more influence on plants from the Creek than on those from the Tamar. This may be explained by the fact that, having a greater concentration of Zn originally, the Creek weed achieved a higher level during the experiment. Following the removal of Zn from the medium, the weed from both sites regained its original rate of growth (roughly 5% per day) and analyses after 12 days in clean water gave mean Zn concentrations of 1600 and 1182 µg/g in the Restronguet Creek and Tamar plants respectively.

Nereis diversicolor

Bryan & Hummerstone (1971, 1973b) observed that worms from Restronguet Creek are more resistant to the toxic effects of Cu and Zn than populations from less-contaminated estuaries such as the Avon (Table 34). Although tolerance is affected by salinity and temperature in both populations, worms from the Creek are consistently more metal-resistant than those from the Avon Estuary (Tables 34 & 35).

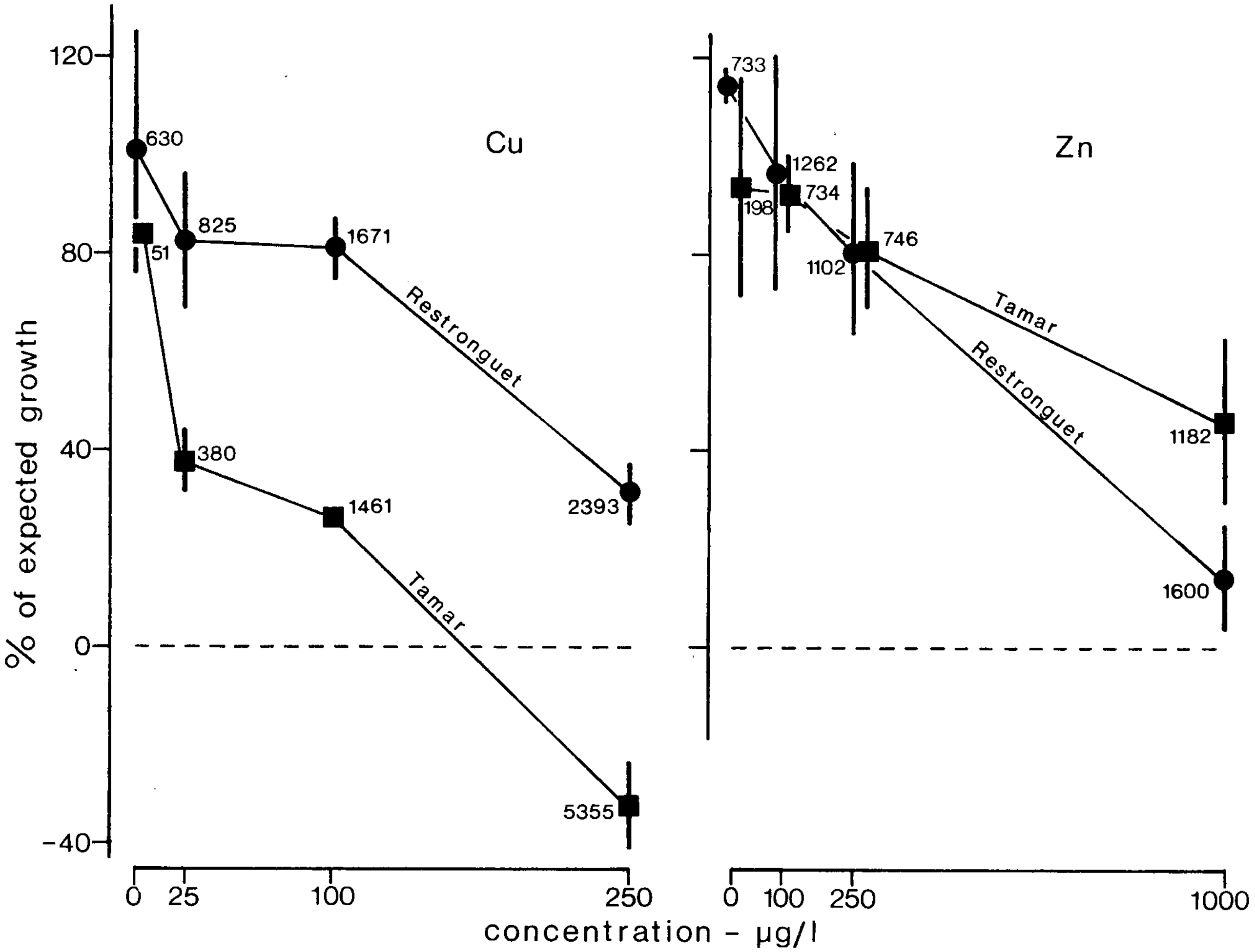

Fig. 18. *Fucus vesiculosus*: effects of Cu and Zn on the growth of small plants from Restronguet Creek and the Tamar Estuary. Plants were grown for 9 days in clean water and for 13 days with metals added. In the controls, growth was almost linear for the 22 day period and the effect of metals is assessed by comparing the measured increase in weight from 9-22 days with that predicted from the first 9 days of growth.

A period of 12 days in clean water was allowed for recovery and the numbers on the graphs refer to the final tissue concentrations after 34 days. Vertical lines show the range of results. Conditions were: salinity 17.5‰; 13°C; continuous light; no nutrients added but media changed regularly.

TABLE 34

NEREIS DIVERSICOLOR: COMPARISON OF LC50 CONCENTRATIONS BETWEEN TWO POPULATIONS

Metal	Salinity ($^{o}/oo$)	96 hr LC50 concentrations (µg/litre) at 13°C	
		Restronguet Cr. worms	Avon worms
Cu (citrate)	17.5	2300	540
Zn (sulphate)	17.5	94000	55000
	3.5	14600	11000
	0.35	2300	1500

TABLE 35

NEREIS DIVERSICOLOR: INFLUENCE OF SALINITY AND TEMPERATURE ON THE TOXICITY OF Cu TO TWO POPULATIONS

Salinity ($^{o}/oo$)	Temperature (°C)	Median survival time (hours) in 1000 µg/litre Cu (citrate) at pH 8.0	
		Restronguet Cr.	Avon Estuary
35	13	156	79
26.25	13	187	78
17.5	13	250	78
17.5	19	193	47
8.75	13	160	48
3.5	13	67	35
1.75	13	8	4

Tolerance to Zn in N. diversicolor is based, in part at least, on the lower permeability of Restronguet Creek worms to the metal (Bryan & Hummerstone, 1973b). In addition, these animals may possess a more efficient excretory system and are able to regulate the body concentration fairly efficiently despite the high ambient levels of Zn (e.g. Table 10).

Unlike Zn, concentrations of Cu in N. diversicolor tend to reflect those of the sediments (p. 31) and the high concentrations found in Restronguet Creek worms are stored in membrane-bound vesicles in the epidermis (Bryan, 1976 ; Brown, 1982) and in the nephridia. Although the capacity to immobilise Cu is important in the tolerant worms, this does not provide a complete explanation for their greater metal-resistance, since animals from some other estuaries store relatively high levels of Cu but are not especially tolerant. Preliminary experiments on this problem were described by Bryan (1976) and have since been repeated.

Juvenile worms (∿ 10 mm long) from the Creek and the Avon Estuary (control) were grown in acid-washed sand for 4 months on a diet of yeast. The tolerance of the grown worms to two levels of dissolved Cu was then compared with that of freshly-collected animals of similar size. Table 36 shows that a large measure of Cu tolerance was retained by the grown Creek worms, although most of the tissues were laid down under Cu-free conditions and the body-Cu level was 19.3 times lower than in fresh worms.

TABLE 36

<u>NEREIS DIVERSICOLOR</u>: COMPARISON OF Cu TOXICITY TO FRESH AND LABORATORY-GROWN TOLERANT AND NON-TOLERANT POPULATIONS

Estuary	Fresh or grown worms	Initial Cu level in worms (µg/g dry wt)	Median survival times (hours) in two concentrations of Cu (sulphate) at salinity 17.5 °/oo and 13°C	
			500 µg/litre	1000 µg/litre
Avon	fresh	15	88	68
Avon	grown	11	-	63
Restronguet Cr.	fresh	1100	>400	150
Restronguet Cr.	grown	57	∿400	103

With the aid of ^{64}Cu, the absorption of Cu was studied in groups of grown and fresh worms exposed to different levels of dissolved Cu: uptake curves obtained at 100 µg/l Cu are shown in Figure 19A. The results, expressed as concentration factors reached after 110 h (Figure 19B), show that similar levels are reached by both types of Avon worms over a range of Cu concentrations. This implies that the rate of uptake is directly proportional to the level of dissolved Cu. Results for the Creek worms are markedly different: the fresh animals absorb ^{64}Cu most rapidly at low Cu concentrations, whereas the corresponding

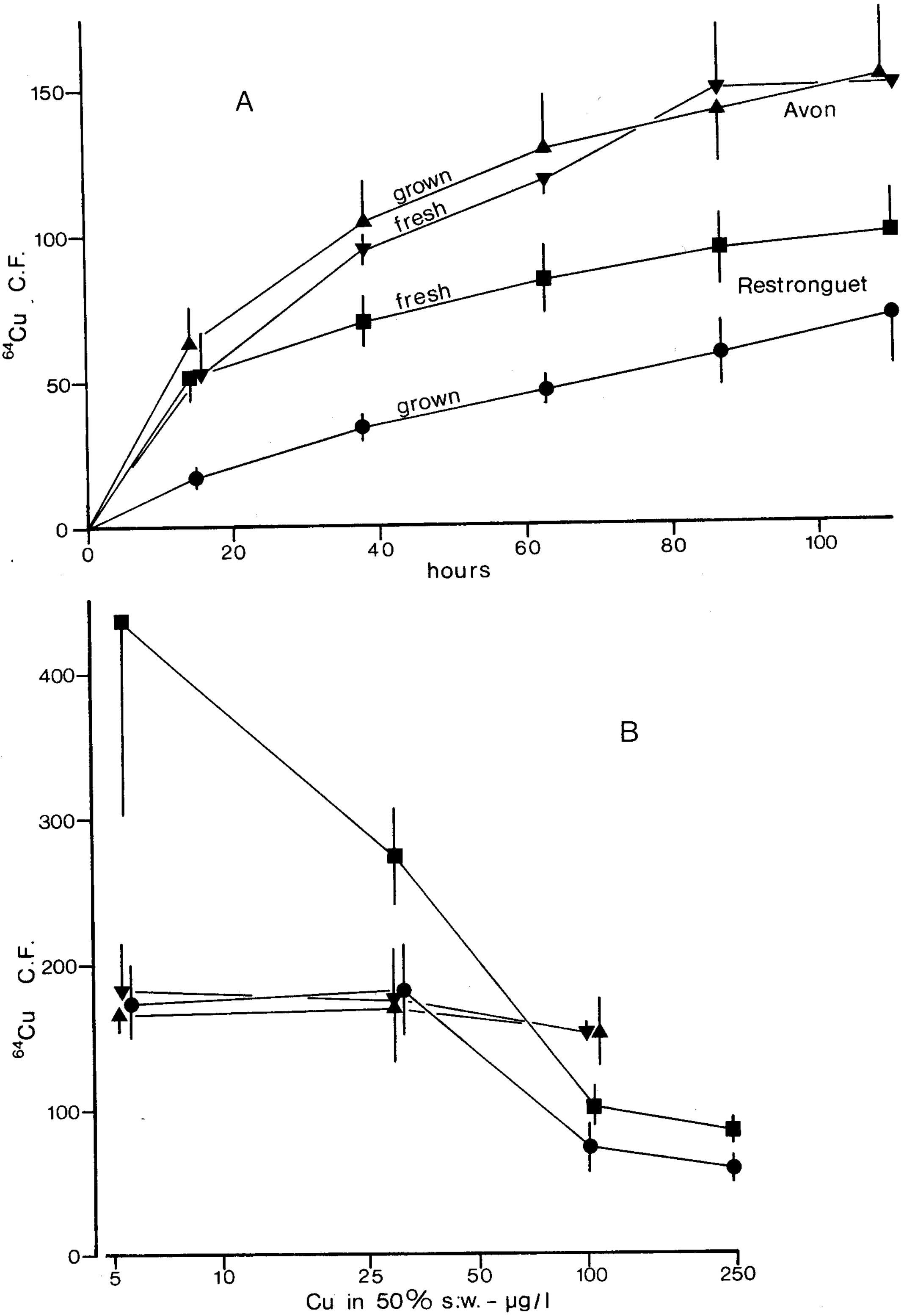

Fig. 19. Nereis diversicolor: (A) Accumulation of ^{64}Cu at 13°C by 4 groups of worms from sea water containing 100 µg/l of stable Cu added as sulphate; (B) Relationships between the amount of Cu added to the water and concentrations factors (CF) on a wet weight basis reached after 110 hours. Values are means and standard deviations for 5 worms.

uptake of Cu by the grown animals resembles that of the Avon worms. Possibly the rapid uptake by the fresh Creek worms is a reflection of the additional binding or exchange capacity of their high-Cu epidermal cells. At 100 µg/l of Cu, a level approaching the threshold of toxicity in Avon worms, the uptake of ^{64}Cu by both groups of Creek animals is, significantly lower. Thus, reduced permeability to Cu appears to be an important factor in raising the threshold of toxicity for this population beyond 250 µg/l. In addition, although not conclusive proof, the retention of tolerance by the grown Creek animals supports the idea that Cu-tolerance is genetically-based. The possession of tolerance is clearly a very important factor controlling the distribution of *N. diversicolor* in the Creek, particularly in areas of low salinity.

Carcinus maenas

During hot weather large crabs are sometimes found at low tide under stones in the acid waters of the Carnon River (site R9). Not surprisingly perhaps, dead crabs have sometimes been seen in the river and others were found in the mud under a sheet of corrugated iron.

Tolerance to Zn. Experiments in which the resistance of Restronguet Creek crabs to Zn was compared with that of other populations showed that they were generally more tolerant. Table 37 compares the median survival times for different-sized crabs from three sites following exposure to 10000 µg/l of Zn. Crabs from the Creek, particularly the larger specimens, are unusually tolerant to dissolved Zn. Analyses of dead crabs for Zn indicated that for the medium-sized animals a net uptake of 440 µg/g

TABLE 37

CARCINUS MAENAS: COMPARISON OF Zn TOXICITY TO DIFFERENT-SIZED CRABS FROM THREE POPULATIONS

Estuary	Median survival times for groups of 10 crabs in 10,000 µg/litre Zn at 35 °/oo salinity and 13°C. Also, net increase in body Zn level in dead crabs					
	Very small (∿ 0.5g wet wt)		Small (∿ 4g wet wt)		Medium (∿ 16g wet wt)	
	MST (days)	Net Zn uptake (µg/g dry wt)	MST (days)	Net Zn uptake (µg/g dry wt)	MST (days)	Net Zn uptake (µg/g dry wt)
Restronguet Cr. (R9)	7.3	325	6.6	297	55*	256‡
Falmouth H. (F16)	3.7	451	4.4	349	7.8	433
Tamar (lower)	3.0	383	3.8	282	6.8	440

*Projected value as experiment finished at 38 days. ‡Dead crabs only - see text.

dry wt of Zn (control 77.5) killed the Plymouth crabs, 433 μg/g (control 67.2) killed the Falmouth Harbour crabs and 256 μg/g (control 136) killed 40% of the Creek crabs. However, the surviving Creek animals had absorbed more Zn, 520 μg/g, in 38d without any obvious effect. If uptake of Zn by the crabs was linear, the net uptake of Zn per day based on the mean time of exposure would be: Plymouth 38.9 μg/g/day, Falmouth 28.1, Restronguet Cr. 20.2 (dead) and 13.7 (survivors).

Table 38 gives the concentrations of Zn in the tissues of crabs which appeared unaffected by 38d exposure to 10,000 μg/l of Zn and compares them with values for normal individuals from the lower Tamar Estuary.

TABLE 38

CARCINUS MAENAS: TISSUE Zn LEVELS IN CREEK CRABS SURVIVING IN sea water containing 10,000 μg/litre OF Zn FOR 38 DAYS

Tissue	Zn-tolerant creek crabs (3)		Tamar crabs (9)	
	μg/g wet wt	μg/g dry wt	μg/g wet wt	μg/g dry wt
Urine	2.7	42.7	0.3	5.2
Blood	68	1075	36	486
Green gland	87	586	21	106
Digestive gland	129	535	55	213
Gills	493	3692	29	210
Vas deferens	38	153	24	96
Leg base muscle	68	314	44	201
Dorsal carapace	269	370	2.7	3.6

Bearing in mind the high level of exposure, several tissues from the tolerant crabs, including blood, muscle, vas deferens and digestive gland, accumulate remarkably little Zn. Higher concentrations in the carapace probably reflect surface adsorption, but levels in the green gland and especially the gills are thought to reflect the roles of these tissues in Zn excretion (Bryan, 1966).

The results above indicate that tolerant crabs from the Creek may be less permeable to Zn, possibly better able to excrete the metal and require more Zn to kill them than non-tolerant individuals.

Previous work (Bryan, 1966) described the uptake and loss of ^{65}Zn by the tissues of the shore crab. Additional experiments were carried out in which the accumulation of ^{65}Zn was measured simultaneously in Restronguet Creek and Tamar animals exposed to different levels of stable Zn. A simple comparison of ^{65}Zn concentration factors achieved at different Zn levels (Table 39) shows that values for the Creek crabs are consistently lower; this supports the contention that they are generally less permeable to Zn than normal individuals.

TABLE 39

CARCINUS MAENAS: COMPARISON OF Zn-65 CONCENTRATION FACTORS (WET BASIS) FOR INTERMOULT MALE CRABS FROM TWO POPULATIONS

Concentration of Zn added to sea water (μg/litre)	Period of exposure (days)	Concentration factors for 1-3g wet wt crabs at 35 °/oo salinity and 13 °C			
		Restronguet Creek		Tamar	
		No.	C.F. ± S.D.	No.	C.F. ± S.D.
0‡	24	3	62.3 ± 5.5	3	149 ± 46
100*	33	5	77.5 ± 27.4	4	110 ± 57
250‡	24	3	28.0 ± 4.5	3	46.3 ± 16.3
1000‡	24	3	18.0 ± 3.0	2	39.0 ± 8.5
1000*	33	6	36.7 ± 9.2	5	54.6 ± 15.8

‡October *January

Unlike the situation for Cu in F. vesiculosus and N. diversicolor, where differences in tolerance between the Creek and other populations are very clear-cut, the results for Zn in C. maenas, a very mobile organism, show more tendency to overlap. Thus, rather than being members of a specially-tolerant population, it is possible that the animals acquire tolerance to high levels of Zn individually as they migrate into the Creek from less-contaminated areas. The gradual acquisition of tolerance may explain the remarkable resistance shown by some larger crabs to 10,000 μg/l of Zn (Table 37).

Tolerance to Cu. Several toxicity experiments demonstrated that the Creek crabs are generally rather more tolerant to dissolved Cu than crabs from the Tamar Estuary. For example, when groups of 20 small crabs (0.4 - 4g wet wt) were exposed to 2000 µg/litre of Cu (sulphate) at a salinity of 35°/oo and 13°C, the median survival times were 8.8 days for the Creek animals and 6.4 days for the controls. However, the former had absorbed less Cu, net uptake 382 µg/g dry wt (initially 260 µg/g) whereas the controls showed a net uptake of 512 µg/g (initially 81 µg/g). Thus, there is an indication that the Creek animals are generally less permeable to Cu and the results of other toxicity experiments support this.

In addition, there is some evidence that the uptake of Cu from the diet may be limited in Cu-tolerant crabs. Unpublished experiments in which high-Cu (∿ 1500 µg/g dry wt) N. diversicolor from the Creek were fed to both Creek and Tamar crabs indicated that the former absorbed only about 6% of the ingested metal compared with about 30% in the latter. As much as 25000 µg/g dry wt of Cu was found in the crab faeces.

In F. vesiculosus and N. diversicolor, the development of tolerance to conditions in the Creek seems to be more essential for Cu than Zn, whereas the need to develop Zn-tolerance appears to be rather more important in C. maenas.

Increased Cu-tolerance in other species

Evidence for increased tolerance to Cu has been observed in other species from the Creek (Table 40) although its development is less obvious than in those organisms already discussed. The amphipod C. volutator is normally very resistant to Cu and thus it is not surprising to find that individuals collected at site R3 on the banks of the Carnon River show a comparatively modest increase in resistance. The polychaetes N. hombergi and the clams S. plana used in the tolerance experiments were from the upper shore at site 6 and were rather less highly exposed to Cu and Zn than some of the species already discussed.

Summary

The possibility that organisms penetrating into the upper reaches of Restronguet Creek possess increased tolerance to metals has been examined in the seaweed Fucus vesiculosus, two polychaetes - Nereis diversicolor and Nephtys hombergi, the clam Scrobicularia plana, and the crustaceans

TABLE 40

COMPARISON OF Cu (CITRATE) TOXICITY TO SPECIES FROM RESTRONGUET CREEK AND OTHER ESTUARIES

Estuary	96 h LC50 (μg/litre)		168 h LC50 (μg/litre)
	Nephtys hombergi (35°/oo; 13°C)	*Scrobicularia plana* (17.5°/oo; 13°C)	*Corophium volutator* (17.5°/oo; 13°C)
Restronguet Cr.	700	4600	50000
*Tamar; ‡Avon	250*	2300‡	32000‡

Corophium volutator and *Carcinus maenas*. Increased tolerance to Cu is found in all six species and increased resistance to Zn is found in *N. diversicolor* and *C. maenas* but not *F. vesiculosus*. Since the area has been heavily contaminated with metals for more than 200 years, there has been plenty of time for metal-resistant populations to develop; and it is suggested that in *N. diversicolor* and *F. vesiculosus*, at least, increased metal-tolerance has a genetic basis. In *C. maenas* it is thought that tolerance may be acquired through exposure to increasing concentrations of Zn or Cu as the crabs migrate upstream. Similar conclusions may apply to other relatively mobile species including *N. hombergi* and *C. volutator*.

Although undoubtedly the mechanisms of tolerance vary in detail from species to species, the development of lower metal permeability seems to be a common feature which presumably allows more time for the detoxication of the metal.

Uptake and effects of metals in transplanted organisms

Experiments were carried out to discover (1) whether organisms from other estuaries can survive at sites in the Creek occupied by native species possessing, initially at least, a greater degree of metal tolerance, and (2) whether in view of the absence of some species from the Creek and the limited distributions of others, adult animals (which are generally less sensitive than young stages) can survive at sites from which they are absent but would be expected to occur if the Creek were 'normal'.

Macroalgae

Fucus vesiculosus and Ascophyllum nodosum were transplanted from the Tamar Estuary (Torpoint) to the lower Creek (site R19) on two occasions (Fig. 20). Both Zn and Cu were absorbed more rapidly by F. vesiculosus than by A. nodosum and in each experiment the former species was in a very poor condition after 7 months compared with the Cu-tolerant native weed from the same site. A. nodosum was not so obviously affected by the conditions and this may be related to its much slower accumulation of both metals. Whether the native A. nodosum is a metal-tolerant strain, or whether the species can acquire metal tolerance, remains unknown. Concentrations of Zn and Cu in the native weed of both species show comparable annual fluctuations: these reflect the higher input during the winter months and also the high level of Zn input observed in the autumn of 1980 (Fig. 6).

Scrobicularia plana

Uncontaminated clams from the lower Torridge Estuary were marked with waterproof ink and transplanted to site R6 which is the upstream limit of native S. plana in the Creek. The clams were unrestricted by netting. At least one animal survived for 280 d and its body levels of Cu and Zn approached those of the natives with Cu being more rapidly absorbed than Zn (Fig. 21). Curiously, in view of the exceptional levels of Cu and Zn in Restronguet Creek, concentrations in S. plana are not particularly remarkable and higher levels have been observed in animals from some other estuaries (Table 14).

Even a short distance down the shore from site R6, no S. plana are found and wide expanses of the Creek mud flats where they would normally be expected are devoid of clams. In the search for an explanation, clams from Penpol (site R13) were moved to sites in the upper and lower Creek where native clams are absent. At intervals the animals were recovered for metal analysis and note was made of the relative proportions of living and dead clams.

Table 41 summarises the results. Mortality was higher at the upstream sites (R7-R9) and was also increased at sites nearer to the channel of the Carnon River (R9 and R16 in Table 41). However, there is no clear evidence from analyses of the survivors (Table 41) that the transplanted clams were killed by the accumulation of Cu or Zn, since

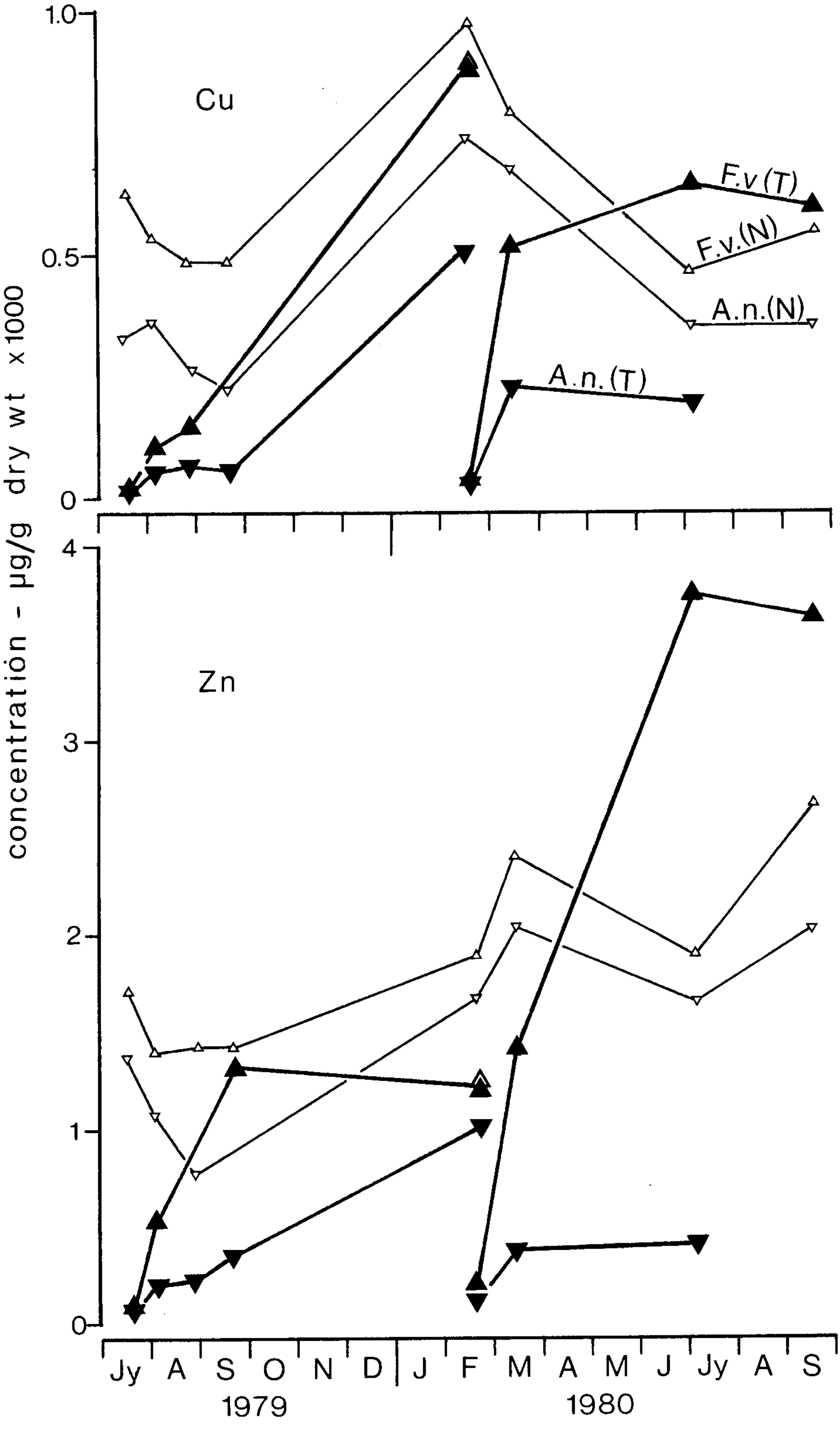

Fig. 20. Fucus vesiculosus (F.v.) and Ascophyllum nodosum (A.n.): absorption of Cu and Zn at site R19 in Restronguet Creek by plants transplanted from the Tamar Estuary (T) on 2 occasions (closed symbols). Open symbols show values for native weed (N). Used tips and first vesicle of A. nodosum, but older frond for F. vesiculosus

similar or higher values have been found in other, apparently unaffected populations (Table 14).

S. plana from the moderately-contaminated Tamar Estuary (Weir Quay) were also transplanted to two sites during these experiments and survived almost as well as the transplanted Penpol animals (Table 41). When, in a later experiment, clams from the relatively-uncontaminated lower Torridge Estuary were used they seemed to be more sensitive than the other populations. However, this may reflect the fact that the experiment started later in the year and thus the stresses of winter, including higher metal inputs, were reached sooner.

There is no clear evidence from the analyses of Penpol S. plana transplanted within the Creek that mortalities are directly related to the accumulation of Cu or Zn. In view of the high levels of Zn and Cu in the waters and sediments of the Creek and their apparent availability to S. plana, it is remarkable that concentrations in these clams are not much higher (see also p. 37). This might be explained if, rather than deposit-feeding on the metallic sediments, the animals suspension-feed at high tide when, because of stratification in the water, relatively clean sea water lies above the sediments. A possible reason for the high mortalities at the most upstream sites R7 - R9 may be that the clams spend so much time avoiding contact with high concentrations of metals in the overlying water that they die from a combination of anoxia and starvation. This is not always borne out by the condition (dry wt and shell length) of the active survivors in Table 41, but was certainly true of many specimens which were found to be moribund and therefore classed as dead. Support for this idea comes from the work of Akberali & Black (1980) who found that S. plana reacted to Cu levels of 10-100 µg/l by closing the shell and only sampled the environment again 2-3h later. Shell closure was also effected by 500 µg/l of Zn or more (Akberali et al. 1981). The fact that these levels of Cu and Zn are typical of Restronguet Creek, certainly gives credence to this explanation.

Cerastoderma edule

Cockles of about 25 mm shell length were collected from the lower Torridge Estuary and placed in groups of 50 in the sediments at four sites (R15 - R18) along transect B in the Creek. Each group was covered with a cage of plastic-covered wire, the edges being buried in the sediment. The accumulation of Cu, Fe and Zn by the cockles is shown in

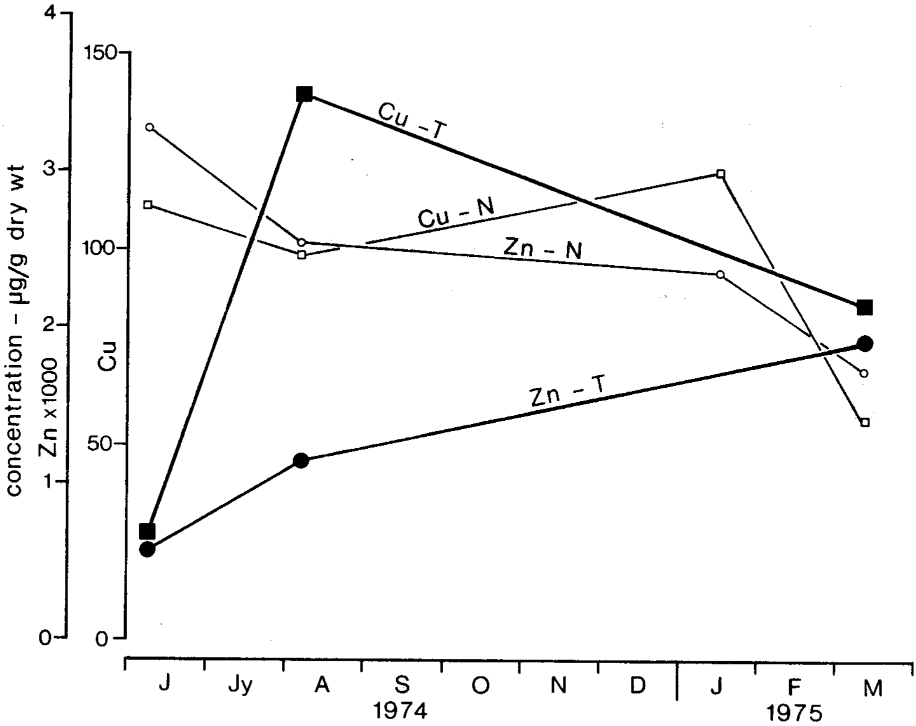

Fig. 21. Scrobicularia plana: changes in concentrations of Cu and Zn in clams transplanted from lower Torridge Estuary to Site R6 (T - closed symbols) compared with levels in native clams (N - open symbols).

TABLE 41

SCROBICULARIA PLANA: CONCENTRATIONS OF Cu AND Zn IN CLAMS TRANSPLANTED TO SITES IN RESTRONGUET CREEK FROM 3 DIFFERENT SOURCES INCLUDING THE CREEK ITSELF (PENPOL)

Clams cleaned for 1 week before analysis

Site	Survival* (%)	Tissue dry wt and length g/mm	Cu (μg/g)	Zn (μg/g)	Survival* (%)	Tissue dry wt and shell length g/mm	Cu (μg/g)	Zn (μg/g)	Survival* (%)	Tissue dry wt and shell length g/mm	Cu (μg/g)	Zn (μg/g)
Penpol natives		Day 0 (Feb. 80)				Day 219 (Sept. 80)				Day 419 (Apr. 81)		
R13	-	0.36/40	56	1515		0.49/44	85	2082	-	0.43/42	62	1711
Penpol transplants		Day 70 (Apr. 80)				Day 219 (Sept. 80)				Day 385 (Mar. 81)		
R9	19	0.37/41	56	2322	0	-	-	-	0	-	-	-
R8	33	0.34/45	74	2577	0	-	-	-	0	-	-	-
R7	86	0.32/41	69	2245	22	$0.26/42^4$	74	2273	0	-	-	-
R16	75	0.41/44	46	1635	86	0.47/43	91	2367	38	$0.34/45^3$	75	2446
R15	-	0.29/44	58	2438	100	0.44/42	97	1952	50	$0.41/41^2$	69	1426
		Day 0 (Feb. 80)										
Tamar natives	-	0.27/40	39	2181	-	-	-	-	-	-	-	-
Tamar transplants		Day 70 (Apr. 80)				Day 219 (Sept. 80)				Day 385 (Mar. 81)		
R8	37	$0.22/43^4$	43	2779	0	-	-	-	0	-	-	-
R16	100	0.28/42	42	2842	36	0.34/40	101	3180	50	$0.35/42^2$	94	4344
						Day 0 (Sept. 80)						
L. Torridge native	-	-	-	-	-	0.32/37	40	477	-	-	-	-
L. Torridge transplants	-	-	-	-		Day 42 (Nov. 80)				Day 166 (Mar. 81)		
R9	-	-	-	-	30	-	71	837	0	-	-	-
R7	-	-	-	-	62	-	55	864	0	-	-	-
R16	-	-	-	-	100	0.39/37	73	636	10	$0.31/38^1$	70	1739
R15	-	-	-	-	100	0.40/37	35	651	37	$0.25/38^3$	91	1533

1-4 = No. of animals used if <5. *Percentage of living clams when all animals recovered from a fraction of transplant area.

Fig. 22. After 63 days, concentrations of 141 µg/g of Cu and 317 µg/g of Zn were reached by cockles at site R18 nearest to the channel of the Carnon River and were comparable with levels found in an apparently healthy native cockle of 35 mm found in the Creek (Table 15). Although only 10-15% mortality was observed after 63 days the remaining cockles died during the next two months (December and January, 1981). A second experiment in March and April 1981 when fresh water and heavy-metal inputs were particularly high (Fig. 6) was concluded after only 26 days. Metal levels in the few surviving animals were similar to those observed previously after 63 days. In both transplant experiments it is thought that swamping by recently-deposited sediment may have contributed to the mortality of the cockles.

In laboratory experiments it was observed that cockles absorbed very little Cu or Zn from Creek sediments covered with flowing sea water. On the other hand, uptake was appreciable if the water was not changed since metals leached from the sediment remained available. This suggests that dissolved metals are the most important source in cockles. After 18 days in sediments covered with unchanged sea water, some cockles had died and levels of 242 µg/g Cu and 404 µg/g Zn were reached in the surviving animals. It appears, therefore, that the toxic body-burden of Cu is somewhere around 250 µg/g. Support comes from the discovery of 486 µg/g of Cu in some moribund 11 mm native cockles (Table 15) of which sediment contamination may account for about 200 µg/g (p. 38). Although probably a contributory factor, it is assumed that Zn is less toxic to cockles than Cu, and this is perhaps borne out by the high value of 787 µg/g of Zn found in the small cockle Parvicardium exiguum dredged from the Carrick Roads (Table 15).

It is concluded that levels of dissolved Cu and Zn in the Creek are generally too high for the prolonged survival of adult cockles, although physical stresses produced by the fine iron oxide-rich surface-sediment may also be a contributory factor.

Mytilus edulis

Groups of 30 mussels of 6-7 cm shell length collected from the Tamar Estuary (Saltash) were placed in cages of plastic-covered wire at 6 intertidal sites (R25, R19, R14, R12, R11, R10) extending from Weir Point to the confluence of the Carnon and Kennall Rivers. Samples, usually of 5 mussels, were taken from each site at intervals over a

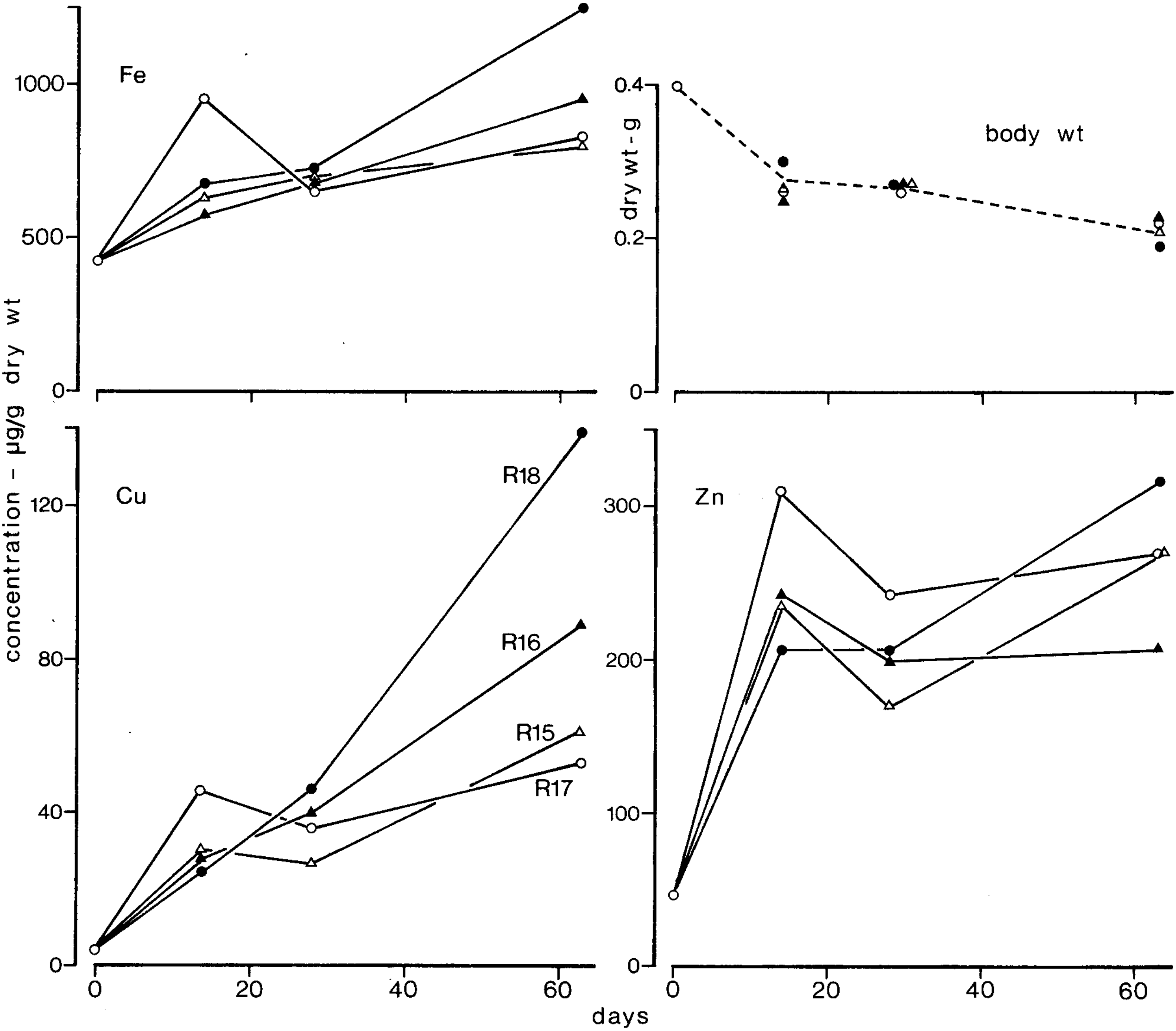

Fig. 22. Cerastoderma edule: accumulation of metals by 25 mm cockles transplanted from the lower Torridge Estuary to transect B (R15-R18) in Restronguet Creek in Sept. 80.

period of 7 months, except at Weir Point where the cage was washed away after 5 months. During the experiment, 33% of the mussels died at sites R11 and R14, 30% died at R10, 17% at R19 and 13% at R12. There was also a tendency for tissue weights to fall during the experiment, but this might be expected in the winter months. Concentrations of Cu, Zn and Fe increased considerably during the seven-month period, although at the end of the experiment, in May, there are signs that concentrations were falling from maxima reached in April when metal inputs were also highest (Figs. 23 & 6). Gonad development was observed in about 20% of the mussels sampled in April and 50% of those surviving until May. The highest values reached in April, after 6 months, are shown in Table 18 and the levels in the bodies and tissues of mussels at the end of the experiment are given in Table 42.

Mussels survived in the Creek better than was expected, especially at the more upstream sites where tissue-Cu concentrations exceeded the 60 µg/g dry weight level estimated by Martin (1979) to be lethal. One reason for this almost certainly depends on the ability of the animals to avoid high levels of dissolved Cu by shell closure. Strömgren (1982) observed that 5 µg/l of Cu induced shell closure in M. edulis, 6-7 µg/l totally inhibited shell growth and 40-80 µg/l represented the 14 day LC50 level: Zn was less toxic and 200 µg/l reduced shell growth by 80%. However, these results refer to continuous exposure to metals whereas, in the Creek, stratification of the water means that exposure to the highest concentrations is intermittent. Sensitivity to increased Cu levels at certain states of the tide would also enable the mussel to avoid exposure to high concentrations of dissolved Zn, and freshly-precipitated Fe which is known to have a deleterious effect on mussels (Winter, 1972). Average ambient metal concentrations at the transplant sites were undoubtedly high, as is indicated by the levels in Fucus vesiculosus from the same sites (Table 7).

Littorina littorea and L. littoralis

More than 200 winkles of each species from the Tamar Estuary (Torpoint) were marked with a file and transplanted to site R19 in the Creek. This site is approaching the upstream limits of distribution of the native winkles. The accumulation of As, Cu and Zn by transplanted L. littorea is illustrated in Figure 24 and shows that uptake occurs mainly during the first two months. Following the uptake phase, fluctuations in concentration

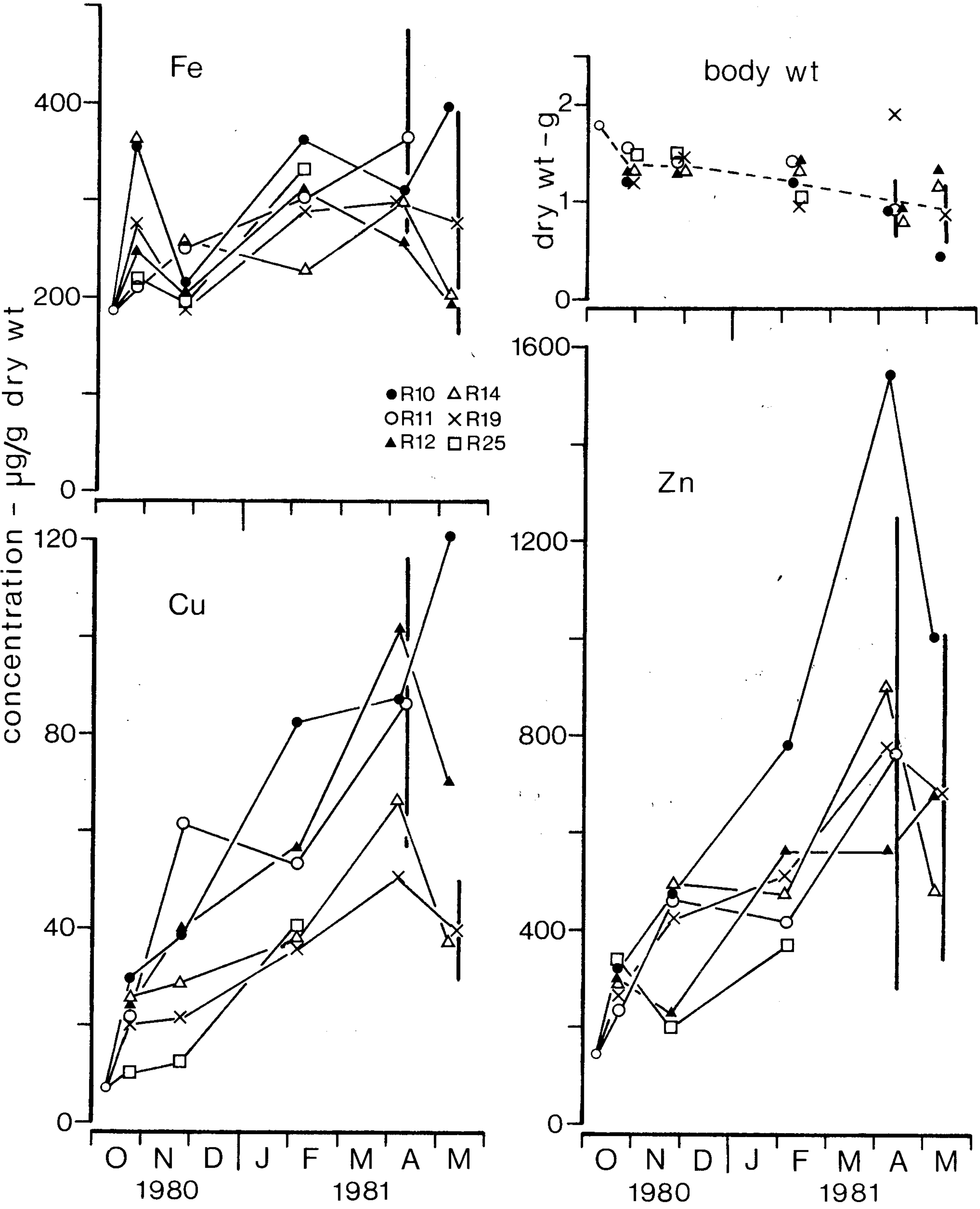

Fig. 23. Mytilus edulis: accumulation of metals in 6-7 cm mussels transplanted to 6 sites in Restronguet Creek from the Tamar Estuary. Vertical lines show standard deviations for 5 animals.

TABLE 42

MYTILUS EDULIS: CONCENTRATIONS IN WHOLE ANIMALS AND TISSUES AFTER 7 MONTHS IN RESTRONGUET CREEK

Animals cleaned for 2 days before analysis.
Byssal threads removed.

Site	No.	Cd	Cu	Fe	Mn	Pb	Zn
		µg/g dry weight					
		whole mussels					
R10	1	7.1	121	399	15.4	31	1004
R12	3	4.1	50	193	6.0	28	670
R14	3	5.7	37	201	5.0	38	480
R19	5	6.5	40	278	9.5	37	674
Original concentrations	10	2.4	7	186	11.6	21	145
		Tissues (site R12)					
Kidneys		-	561	925	-	-	29160
Digestive gland		-	53	573	-	-	146
Gills		-	259	304	-	-	138
Mantle		-	55	446	-	-	81
Foot & muscle		-	21	150	-	-	110
Adductor muscles		-	5.7	130	-	-	114

were observed over the next 10 months. Comparable variations were observed for Cu and Zn in *F. vesiculosus* from the same site indicating that both species were responding to fluctuations in the input of dissolved metals to the Creek, albeit perhaps indirectly through the algal diet in the winkle. It appears that *L. littorea* from the Tamar Estuary can, to a large degree, adapt to the conditions in the lower Creek. This may indicate that the native animals do not represent an especially metal-tolerant strain of winkle but migrate into the Creek from less contaminated localities. More detailed, studies on the native winkles have been carried out recently (Bryan *et al.*, 1983; Mason & Simkiss, 1983), but as yet no toxicity experiments have been carried out to see whether the native animals possess increased tolerance and whether this can be induced in transplants.

Transplant experiments involving *L. littoralis* gave essentially

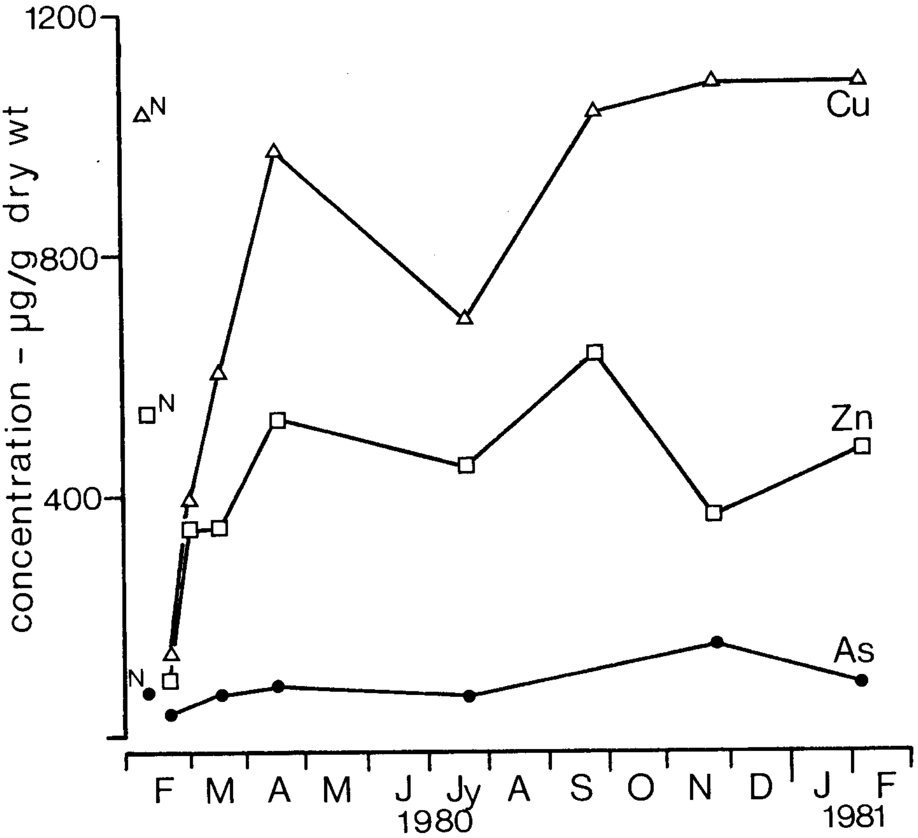

Fig. 24. Littorina littorea: accumulation of Cu, Zn and As by winkles transplanted from the Tamar Estuary to site R19 in Restronguet Creek. Levels in native winkles indicated by N.

the same results, but no animals definitely identified as transplants were found after 7 months. Since the movement of these smaller winkles was not restricted, it remains uncertain whether they migrated, were eaten by crabs or killed by the conditions. Additional work on heavy metals in this species from the Restronguet Creek and other estuaries has been described by Bryan (1983).

GENERAL DISCUSSION

Heavy metals in the environment

The most important source of heavy metals in the Fal System is the Carnon River which drains acidic mine waste water into Restronguet Creek. Concentrations of metals in the River are abnormally high, but levels of Zn are exceptional and often exceed 10000 µg/l. Interactions between River water and sea water in the Creek lead to the flocculation and deposition of Fe, probably as the hydrated oxide. Other elements, including Cu, As, Pb, and a small proportion of the Zn are also deposited probably due to adsorption by the Fe oxide and, in the case of Cu at least, by adsorption to humic substances (see p. 23). These elements, together with Ag and Sn which enter the Creek largely in the particulate phase, become enriched in the sediments and reach concentrations exceeding 'normal' estuarine levels by factors of about 10 for Pb, 40 for Ag and Zn, and 100 for Cu, As and Sn. Elements that tend to remain in solution in the Creek include Cd, Co, Mn, Ni and Zn but only Zn, by virtue of its very high input, is appreciably enriched in the sediments.

A comparable study has been carried out by Foster et al (1978) in Dulas Bay, Anglesey, which receives acid mine wastes via the Afon Goch. They concluded that losses of Cu and Zn from solution occurred by adsorption onto hydrated ferric oxide above pH values of 4.5 and 6 respectively. As in the present work, Mn remained in solution and was not deposited.

The use of chemical extraction procedures on the Creek surface sediments indicate that with the exception of Sn, which occurs mainly as cassiterite, most of the enriched elements are potentially bioavailable. In addition, concentrations of Cu and Zn in the interstitial water from surface sediments are comparable with the high levels found in the overlying water.

Bioaccumulation of heavy metals

The biota of Restronguet Creek is exposed to abnormally high concentrations of Zn, Mn, Cu, Cd and probably Co and Ni in solution: it is also exposed to high levels of Fe, Zn, As, Cu, Sn, Pb and Ag in suspended particles and sediments. The availability of these elements to the biota depends not only on chemical speciation in the waters and sediments, but also on the life-styles of different organisms: thus deposit-feeding bivalves are exposed to metals in a different way from macroalgae. In addition, the levels to which organisms accumulate metals depend not only on ambient metal concentrations but on their various metabolisms.

Bryan & Hummerstone (1973a) found that levels of Cu and Zn in *Fucus vesiculosus* from the Fal System tend to reflect the concentrations dissolved in the water. Experimental work with the same species has shown that, when the metals are used individually, concentrations of Cd, Co, Ni and Pb in the weed reflect those in the water (Bryan, 1983 and unpublished). However, although inputs of these metals to the Creek are abnormally high, they are not generally reflected by levels in the weed, if increased values for Pb due to particulate contamination are excluded. This point will be discussed with regard to Cd, but may apply to other metals also.

The mean concentration of Cd in the Carnon River as it enters the Creek is about 26 μg/l and, since its behaviour in the water is almost perfectly conservative, values of several μg/l are found even in the more saline waters. Levels of the same order in the waters of the Bristol Channel and Severn Estuary have led to Cd levels in *F. vesiculosus* at least an order of magnitude higher than those in the Creek (Morris & Bale, 1975). It has been shown experimentally that Cd absorption by the weed is reduced by high levels of Zn (Bryan, 1983), and this provides an explanation for the anomaly, since the ratio of Zn to Cd in the Severn Estuary is about 10:1 compared with 400:1 in Restronguet Creek. In addition to Zn, competition from dissolved Mn and Cu in the Creek probably assists in suppressing the accumulation of Cd by the weed. The contrast between levels of Cd in the biota of the two estuaries seems to be general and applies at all trophic levels. The differences are particularly obvious in gastropod molluscs, since levels in animals from the Creek are lower by factors of 1-2 orders of magnitude (Tables 21-24). These observations on Cd are very relevant to the setting of emission standards for estuaries and support the contention that if there are limits for metals they should not be uniform but tailored to the capacity of the individual estuary to receive them.

The surface sediments in Restronguet Creek contain metals in particulate and dissolved forms which are bioavailable to various species. For example, if the sediment is covered with clean, aerated sea water, Cu and Zn are leached into the water and quite high concentrations are reached (see p. 58). There is good evidence that the sediment is an important source of Cu in N. diversicolor although it remains uncertain as to whether the body surface or the gut is the principal route for uptake. Concentrations of Cu in N. diversicolor (Luoma & Bryan, 1982) and Perinereis cultrifera (Fig. 11) relate very closely to sediment Cu levels and values exceeding 1000 μg/g have been observed in worms from the Creek. On the other hand, Luoma & Bryan (1982) were unable to relate concentrations of Cu in the deposit-feeding clam Scrobicularia plana to those of the sediments, and animals from the Creek contain far less Cu (∿100 μg/g) than might be expected from the sediment levels (∿3000 μg/g). This clam occurs only on the margins of the mudflats and probably avoids the worst conditions by shell closure, feeding only when a wedge of relatively uncontaminated water covers the mudflats. Similarly, it is thought that shell closure in response to high levels of Cu and Zn in the water enabled transplanted Mytilus edulis to survive for at least 7 months in the upper reaches of the Creek. Another reason for the relatively low level of Cu in S. plana may be the limited availability of this metal in the sediments despite its high total concentration. It is thought that high levels of hydrated Fe oxide in the Creek sediments adsorb some elements, including Cu, so effectively that their availability to S. plana in the Creek is lower than might be predicted from the total sediment concentrations (Luoma & Bryan, 1982). For example, it has been demonstrated that concentrations of As and Pb in S. plana are related directly to the As/Fe and Pb/Fe ratios in 1N HCl extracts of oxidised surface sediments rather than to the levels of As and Pb alone : thus, as the amount of extractable Fe increases, the availability of the other elements is reduced (Langston, 1980; Luoma & Bryan, 1978).

So far, only the influence of external factors on bioaccumulation has been considered. However, the metabolism of metals by the organisms themselves is very important in controlling the concentrations ultimately accumulated.

Levels of Zn in the Carnon River as it enters the Creek are about 1000 times higher than 'normal'. However, this high level of contamination is reflected only slightly by increased concentrations of Zn in polychaetes, crustaceans and fish because they are able to regulate the metal, i.e. increased absorption of Zn from the environment is counteracted by more efficient excretion. On the other hand, in macroalgae and bivalve molluscs, the regulation of Zn is less effective, since rather than being excreted with greater efficiency the metal is detoxicated and stored in particular tissues. In bivalves, for example, Zn is stored in the blood cells (amoebocytes) of Ostrea edulis (Table 17; George et al., 1978), in the kidneys of M. edulis and the scallop Chlamys varia (Tables 42 & 20), and in the digestive gland of S. plana (Table 13).

Generally-speaking, Cu is less effectively controlled than Zn, although its regulation is evident in several species including the shore crab Carcinus maenas and the flounder Platichthys flesus. Exceptional concentrations of Cu are accumulated by other species, including macroalgae, some polychaetes, and molluscs, such as oysters, and reflect not only the high level of Cu contamination in the Creek but also the efficiency of the organisms' detoxication systems. Thus Cu is stored in the amoebocytes of oysters (Table 17), in the pore cells of Littorina littorea (Mason & Simkiss, 1983), and in the epidermis of Nereis diversicolor (Bryan & Hummerstone, 1971).

In addition to Zn and Cu, other elements which are regulated by some species include Mn and Fe, in polychaetes for example (p. 36). Further, Klumpp (1980) reported that winkles Littorina littoralis from the Creek are able to regulate body As levels at high levels of exposure. Regulation of As is also evident in other species including the worm Tharyx marioni in which concentrations of 2000 μg/g can be regarded as 'normal' (Gibbs et al., 1983).

It seems to be generally true that essential elements including As, Cu, Mn, Fe and Zn are better regulated than non-essential elements such as Ag, Cd and Pb. Thus studies on species from the Fal System have proved very useful in identifying tissues in which particular metals are regulated and may therefore have essential roles. As metalloproteins or metal-protein complexes, trace metals usually occur in enzymes or in oxygen carriers such as the Cu-protein haemocyanin. Recently, however, it has been shown that the jaws of nereid polychaetes contain about 1.5% of Zn and, since the concentration is unaffected by environmental levels in the Creek, it is postulated that Zn is involved in hardening the jaw surfaces (Bryan & Gibbs, 1980). A similar conclusion was drawn for the role of Cu in the jaws of glycerid polychaetes in which 13% of Cu was found in the jaw tips (Gibbs & Bryan, 1980). In the polychaete Melinna palmata, around 1.5% of Cu is found in the gills and appears to be involved in a chemical defence mechanism for deterring small predatory fish (Gibbs *et al.*, 1981).

It is concluded that concentrations of heavy metals in species from Restronguet Creek do not always reflect the high environmental levels to which they are exposed. There are various reasons for this, some of which relate to physico-chemical conditions in the Creek. Thus the accumulation of relatively low levels of Cd in the biota, despite its high input to Restronguet Creek, appears to result from competition for absorption sites from high concentrations of other dissolved metals in the water, particularly Zn. Other reasons relate to the characteristics of individual species. In molluscs, for example, exposure to the highest environmental concentrations can be avoided by shell closure. Also, some animals are able to regulate concentrations of metals such as Zn in the body against environmental changes. However, although this gives the impression that the organism is not exposed to contamination, it may in fact be struggling to excrete the metal from the body fast enough to balance increased absorption. Thus in species that regulate metals it may be difficult to judge from levels in the tissues whether or not the organism is exposed to toxic concentrations.

Effects of metals in Restronguet Creek

Of the dissolved metals in the waters of the Creek only Cu (∿10-100 µg/l) and Zn (∿100-2000 µg/l) occur at concentrations which are likely to produce significant environmental effects. In support, experiments on the toxicity of diluted Carnon River water to the small bivalve *Abra tenuis* indicate that its toxicity depends largely on the additive effects of Cu and Zn. Also, concentrations of several thousand µg/l of Fe, precipitated as the hydrated oxide, are suspended in the waters of the Creek and concentrations of this order have been observed to increase the mortality of *M. edulis* under experimental conditions (Winter, 1972). Other elements in the water, including As, Cu, Pb and Zn, are adsorbed by the Fe oxide and might considerably enhance its effect on filter-feeding organisms. Concentrations of Fe in the surface sediments are usually 5-6%, approximately double the values for less contaminated estuaries, and levels of Cu, Zn, As and Sn in the sediments are of the order of 1500 to 3500 µg/g. Based on their toxicities in solution (Table 29), sediment Cu would be expected to have far more impact than either Zn or As, whilst the presence of sediment Sn largely as cassiterite renders it unlikely to exert any impact.

A comparison between the fauna of the Creek and that of other tributaries of the Fal System has shown clearly that it is impoverished in molluscs, especially bivalves. This is not surprising, since embryonic and larval bivalves are very sensitive to Cu and Zn at concentrations commonly found in the Creek (Table 29). In addition, surface sediments from the upper reaches of the Creek proved lethal to juvenile bivalves including S. plana and Macoma balthica under experimental conditions and Cu appeared to be the metal having the most impact. Although the tolerance of adult organisms to metal toxicity generally exceeds that of juveniles and larvae, transplanted adult C. edule were killed by exposure for several months in the lower reaches of the Creek, although whether accumulated Cu and Zn was the cause of death remains uncertain. Some individuals of M. edulis, transplanted to the upper reaches of the Creek, survived for at least 7 months despite losing weight and absorbing high concentrations of Cu and Zn. S. plana is the only bivalve occurring in any numbers in the Creek, but is confined to the upper margins of the mudflats and does not survive within 150 metres of the River Channel. When native clams were moved nearer to the River at transect A they died within a matter of weeks, but at transect B, in the lower reaches, some individuals survived for at least a year. The transplanted native clams showed little evidence for the accumulation of additional Cu and Zn, and it is postulated that mortality may have been caused by starvation and anoxia resulting from an attempt by the clam to remain closed and thus avoid the worst of the conditions. It is remarkable that larvae of S. plana ever became established in the Creek, although the predominance of large specimens in the population suggests that successful recruitment is rare. Since S. plana in the Creek probably spawns mainly in July and August a dry autumn with minimal metal inputs might provide the most favourable conditions for settlement.

Of the gastropods that might be expected in the vicinity of the Creek, Hydrobia ulvae is the most obvious absentee. Nucella lapillus and Patella vulgata occur at, or just outside, Restronguet Point, but winkles Littorina littorea, L. littoralis and L. saxatilis occur in the lower reaches of the Creek.

Since the very young stages of organisms are usually most sensitive to metal toxicity, it is thought that many of the more mobile species including gastropods, some errant polychaetes, for example Nephtys hombergi and Glycera convoluta, and crabs Carcinus maenas colonise the

Creek by migration from less contaminated areas. Toxicity experiments have demonstrated that N. hombergi from the Creek possess greater tolerance to Cu than 'normal' individuals, whilst increased tolerance to both Zn and Cu has been observed in C. maenas. Although this might reflect the selection of the most tolerant individuals by the conditions in the Creek, it is thought that the greater tolerance may also be acquired through exposure as the organisms migrate into the Creek. Under experimental conditions, the induction of Cu tolerance through exposure to sublethal concentrations has been observed in the polychaetes Neanthes arenaceodentata (Pesch & Hoffman, 1982) and Eudistylia vancouveri (Young & Roesijadi, 1983).

The distributions of several species within the Creek appear to be virtually 'normal' and are thought to depend on the presence of metal-tolerant strains. One example is N. diversicolor which possesses increased tolerance to both Cu and Zn and is able to survive at upstream sites where salinities are low and dissolved metal concentrations are high. In this context it may be significant that the larvae of N. diversicolor undergo a direct development without a true pelagic phase (Dales, 1950): since the juveniles remain in the adult environment, selection for metal tolerance can be expected to be operative from an early stage. Similarly, the presence of a widespread 'resident' population of Pygospio elegans within the Creek may be attributed to this species' habit of larval brooding:, however, metal tolerance remains to be investigated in this small-sized species. F. vesiculosus, which survives in the upper reaches of the Creek despite accumulating several thousand µg/g of Cu and Zn, may be another example of an especially tolerant strain.

The occurrence of very high concentrations of metals in some tolerant species may pose problems to other organisms. Predation by birds on some invertebrates from Restronguet Creek (plus adhering sediment) could result in their ingesting high levels of Cu and sometimes Zn or As. For example, Redshank, Tringa totanus, are winter visitors to the Creek and feed almost exclusively on N. diversicolor containing a high concentration of Cu. Since its daily intake of worms is roughly equal to its body weight (Goss-Custard, personal communication), the Redshank may be at risk in the Creek, and this is being studied.

To summarise:-

Although Restronguet Creek is heavily contaminated with toxic metals such as Cu and Zn, it has a flora and fauna which is less obviously affected than might be predicted from toxicity data in the literature. Among the most important reasons for this appears to be the development in some species of metal-tolerant strains, thus enabling them to maintain breeding populations in the Creek. In addition, other species although not necessarily breeding there are able to migrate into the Creek from other less contaminated areas of the Fal System. Some of these species show evidence of greater tolerance to Cu and Zn which may have been induced by increasing exposure to these metals. The most obvious absentees from the Creek macrofauna are bivalve molluscs, the larvae and juveniles of which appear unable to withstand the high concentrations of Cu, Zn, and perhaps recently-precipitated Fe oxide, in the waters and sediments of the Creek. An exception to this is the deposit-feeding clam S. plana, although its distribution is strictly limited to the upper margins of the Creek mud flats.

Many tolerant species occurring in the Creek contain much higher concentrations of metals than organisms from 'normal' estuaries. Thus predators (fish, birds) feeding within the Creek have high metal intakes.

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APPENDIX

MARINE FAUNA OF THE FAL ESTUARY

The following is a summary list of those species identified from samples taken in 1979-80 in the northern and central parts of the Fal Estuary and which are mentioned in the text. Metal levels are given in the text for those species shown with an asterisk.

COELENTERATA

Edwardsia callimorpha (Gosse)
**Actinia equina* L.
**Tealia felina* (L.)
Sagartiogeton undata (Müller)

ECHIURA

Thalassema thalassemum (Pallas)

PHORONIDA

Phoronis psammophila Cori

ANNELIDA

Aphrodita aculeata L.
Sthenelais boa (Johnson)
Pholoe minuta (Fabricius)
Phyllodoce spp.
Eulalia spp.
Ophiodromus flexuosus (D. Chiaje)
Syllidia armata Quatrefages
**Nereis diversicolor* O.F. Müller
**Perinereis cultrifera* (Grube)
Platynereis dumerili (Aud. & M. Edw)
**Nephtys hombergi* Lam.
Nephtys cirrosa Ehlers
**Glycera convoluta* Keferstein
Scoloplos armiger (O.F. Müller)
Pygospio elegans Claparède
Polydora spp.
Prionospio malmgreni Claparède
Streblospio shrubsoli (Buchanan)
Magelona alleni Wilson
**Cirriformia tentaculata* (Montagu)
Caulleriella caput-esocis (St. Joseph)
Caulleriella sp.
**Tharyx marioni* (St. Joseph)
Notomastus sp.
Myriochele sp.
Ampharete acutifrons (Grube)
**Melinna palmata* Grube
Manayunkia aestuarina (Bourne)
Megalomma vesiculosum (Montagu)
Myxicola infundibulum (Renier)
Pomatoceros triqueter (L.)
Serpula vermicularis L.
Peloscolex benedeni (Udekem)

CRUSTACEA

Balanus balanoides (L.)
Eliminius modestus Darwin
Chthamalus stellatus (Poli)
Janira maculosa Leach
Gammarus zaddachi Sexton
Marinogammarus marinus (Leach)
Marinogammarus obtusatus (Dahl)
Marinogammarus finmarchicus (Dahl)
*_Corophium volutator_ Pallas
Crangon crangon (L.)
Pagurus bernhardus (L.)
*_Carcinus maenas_ (L.)
Macropipus arcuatus (Leach)
Macropipus depurator (L.)

MOLLUSCA

*_Littorina littorea_ (L.)
*_Littorina littoralis_ (L.)
Littorina saxatilis (Olivi)
Hydrobia ulvae (Pennant)
*_Crepidula fornicata_ (L.)
*_Nucella lapillus_ (L.)
*_Ocenebra erinacea_ (L.)
*_Buccinum undatum_ L.
*_Nassarius reticulatus_ (L.)
Philine aperta (L.)
Akera bullata Müller
Mytilus edulis L.
Ostrea edulis L.
Anomia ephippium L.
*_Chlamys varia_ (L.)
Thyasira flexuosa (Montagu)
Mysella bidentata (Montagu)
*_Cerastoderma edule_ (L.)
*_Parvicardium exiguum_ (Gmelin)
*_Venus striatula_ (da Costa)
*_Venerupis aurea_ (Gmelin)
*_Venerupis pullastra_ (Montagu)
Abra alba (Wood)
Abra nitida (Müller)
Abra tenuis (Montagu)
*_Scrobicularia plana_ (da Costa)
*_Macoma balthica_ (L.)
Mya arenaria L.

PISCES

*_Platichthys flesus_ (L.)

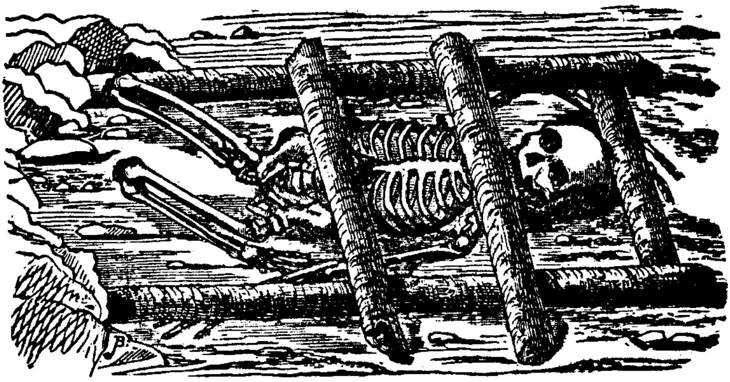
SKELETON

Discovered resting on the TIN-GROUND

Between Tarnon-dean and the Arsenic-works, Perran-ar-Worthal.

Drawn by Mr. H. M. Geoffroi.

From a Sketch by the late Reverend Canon Rogers, M.A., of Penrose.



From Henwood (1873)