1999

RESPONSES OF RECENT BENTHIC FORAMINIFERA TO METAL POLLUTION IN SOUTH WEST ENGLAND ESTUARIES: A STUDY OF IMPACT AND CHANGE

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http://hdl.handle.net/10026.1/2134

http://dx.doi.org/10.24382/4300
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RESPONSES OF RECENT BENTHIC FORAMINIFERA TO METAL POLLUTION IN SOUTH WEST ENGLAND ESTUARIES: A STUDY OF IMPACT AND CHANGE

by

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A thesis submited to the University of Plymouth in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Department of Geological Sciences
Faculty of Science

November 1999

RESPONSES OF RECENT BENTHIC FORAMINIFERA TO METAL POLLUTION IN SOUTH WEST ENGLAND ESTUARIES: A STUDY OF IMPACT AND CHANGE

SHEILA JOAN STUBBLES

Abstract

There was a major discharge into Restronguet Creek, south-west Cornwall in January 1992 of metalled acidic mine water drainage from the recently closed Wheal Jane tin mine. Shortly after this discharge a post-impact study using the responses of Recent benthic foraminifera as indicators of metal pollution was carried out on this Creek which had not been investigated previously. Because of a lack of pre-discharge foraminiferal data from Restronguet Creek, other estuaries, which previously drained metal mining regions, have been sampled in order to determine the background levels in foraminiferal populations. These estuaries, Fowey (Cornwall), Avon and Erme (south-west Devon) have not been investigated previously. The research programme included reconnaissance sampling of the estuaries Looe, Yealm, Kingsbridge, Axe and Carrick Roads (south-west England), primarilly to determine the geographical distribution of the agglutinated species. In all, 651 samples were taken for micropalaeontological and laser analysis from which an estimated 260,000 tests have been picked and some 70 species identified. A further 395 samples were taken for metal, carbon, nitrogen, sediment grain size and mineralogical analysis.

The results of this research show changes over time with the colonisation of barren stations, increased abundance of living individuals, reduced proportions of deformed tests, less severe acid dissolution of the test walls and a seasonal species distribution which is similar to that of the Fowey Estuary. Low diversity is unchanged and the agglutinating foraminifera, which form distinct assembage zones in the control estuaries, remain absent from Restronguet Creek. The data provided by the short cores from Restronguet Creek suggest that the 1992 discharge does not account for the absence of these species.

During the period of investigation the sediment-bound metals in terms of the concentrations have, in general, increased but the river water quality entering the Creek has improved in terms of metals and acidity. This suggests that the foraminifera are more directly influenced by metals in solution and that tangible benefits have been gained from the water quality improvement programme inaugurated by the Environment Agency.

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Acknowledgement

In carrying out this research it was my primary intention to demonstrate the application of Recent benthic foraminifera as indicators of metal polution, particularly in an area renowned for its mining past. Ultimately, it is hoped that our knowledge of these organisms may have been advanced by this research.

The scholarship that financed much of this research was generously provided by the Harold Hyam Wingate Foundation and ensured its completion. I gratefully acknowledge the assistance and kindness shown by the Trustees and Jane Reid (Administrator). I thank my friends and family for their patience and support shown over the many years of hard work which at times has been frustrating. The guidance and support of my three supervisors Malcolm Hart, John Green and Colin Williams is much appreciated. I also acknowledge, with fond memories, the support and guidance given by Dr. Steve Caswell during the early days of this research. The support given by the technical, academic and secretarial staff in the Department of Geological Sciences and within the Faculty of Science in general, is also acknowledged. I thank those land owners who allowed access to their land, most particularly Mr A. J. B. Mildmay-White of the Flete Estate. I hereby thank skipper Dave Scott for providing his boat and expertise for the boat surveys and his wife Lin for excellant B and B provision. I acknowledge the assistance given by Nick Bailey who identified many of the plant names, Andy Fisher and his team for the geochemical analysis, Bob Head (PML) who guided me through the carbon analysis and allowed me to use his nanno-balance, Bob Clarke and Mike Candle for their assistance with PRIMER, Simon Chenery (British Geological Survey) who operated the laser ablation ICP, Roy Moate, Jane Green, Pete Bond and the late Derek Sargeant (EM unit) for support, cups of tea and film negative development, Tony Smith and Dave Griffiths (Media) for supplying superb slides and plates over the years, Paul Russel (Biological Sciences), Richard Hartley (Geographical Sciences) for assistance with the sediment grain size analysis, Bill Langston (PML) for advise on the geochemical method to use, John Whittaker who enabled access to the Heron-Allen and Earland, and Williamson Collections at The Natural History Museum in London and Clive Jones (The Natural History Museum in London) for carrying out the palaeovision imaging.

I acknowledge the input of my two examiners, Professor John Haynes and Dr Malcolm Nimmo. Their constructive criticisms, suggestions and validation of my integrated, interdisciplinary approach has been much appreciated. I will endeavour to develope those post-doc issues which they raised during the examination.

Finally, "Never mind the quality, feel the width." From the Rag Trade, BBC TV, circa. 1960.

AUTHOR'S DECLARATION

At no time during registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

This study was financed with the aid of a scholarship from The Harold Hyam Wingate Foundation, and, small grants from the Womens Graduate Association and the University of Plymouth.

A programme of advanced study was undertaken.

Relevant scientific seminars and conferences were regularly attended at which work was often presented; external institutions were visited for consultation and to use their resources.

Signed ..S.J.Stubbles..........
Date....19. 11.99..................

Four refereed papers have been published, copies of which appear at the end:

Stubbles S.J. Recent benthic foraminiferida as indicators of pollution in Restronguet Creek, Cornwall. *Note of Poster Display at the Annual Conference of the Ussher Society*, 200-204.

Stubbles S.J. 1995 Seasonal variation in agglutinated foraminifera standing crops in the marsh and tidal flats of the River Erme, Devon. In: *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera*, Kraków, Poland, Kaminski M.A., Geroch S. and Gasinski M.A. (ed.) (Grzybowski Foundation Special Publication), **3**, 265-270.

Stubbles, S.J., Green, J., Hart, M.B. and Williams, C.L. 1996. Response of foraminifera to the presence of heavy metal contamination and acidic mine drainage. *Minerals, Metals and the Environment II.* Prague. Special Publication, 217-235. Institute of Mining and Mineralogy, London.

Stubbles, S.J., Hart, M.B., Williams, C.L., and Green, J.C. 1996. The ecological and palaeoecological implications of the presence and absence of data:evidence from benthic foraminifera. *Proceedings of the Ussher Society,* **9**, 54-62.

Chapter One

Introduction

1.1 Introduction - aims and objectives

In January 1992 there was a major discharge (Figure 1.1) of metal-rich acidic water from Wheal Jane tin mine into the Carnon River (full details, Section 1.5.2), via. Clemows Stream tailings lagoon (Figure 1.2). The aim of this research is to document the effects of this discharge on the ecology of benthic foraminifera in the marginal marine environment of Restronguet Creek (Figure 1.3, Enclosure 1a), where the Carnon River discharges into the Fal Estuary.

Benthic foraminifera are used as environmental indicators because they often occur in very high abundances (Alve, 1995a), have short life cycles and may show a rapid and specific response to stress. They are potentially reliable *in situ* indicators of environmental stress because of their low motility. The main objectives of this research are, therefore, to use the changes in benthic foraminiferal ecology (standing crop densities, low diversity, loss of species, changes in faunal dominance, levels of test deformity and, specifically, the etching of tests by acidic waters) to determine the post-impact effects of acid mine drainage (AMD). In addition, geochemical analysis of surface sediment samples has determined concentrations of potentially available metals. A relatively new technique, Laser Ablation Inductively Coupled Plasma, has also been used to determine metal concentrations within the tests of the foraminifera. This technique has much lower detection limits compared with SEM microprobe analysis and does not rely upon bulk analysis but is applied to individual tests and chambers. Hence, the unknown variables that exist between individual tests may be ignored (Boyle, 1995). Sediment grain size and mineralogical distribution, carbon analysis and the carbon-nitrogen (C/N) ratio have also been determined. These variables contribute additional information on the distribution of the agglutinating foraminifera and the adsorption potential of mineral grains which may affect the concentration of sediment-bound metals. Water quality data have been provided by the Environment Agency (previously the National Rivers Authority) and these data are used to support conclusions with respect to the dynamic spatial and temporal changes exhibited by the foraminifera in response to improvements in river water quality entering Restronguet Creek.

The region drained by the Carnon and Kennell Rivers (Figure 1.3) has undergone centuries of metalliferous mining (Section 1.5.1) with Restronguet Creek suffering severe levels of pollution and physical disturbance relative to the other sample locations. Historical research has shown that the depth of sediment contamination in Restronguet Creek must be great and represents some 3,000 years of mining (Section 1.5.1). South West England is rich in metalliferous rock formations and, therefore, background levels of metals in run-off and drainage water will be high relative to other areas of the UK. Hence, for the present study only estuaries in Devon and Cornwall are considered to be appropriate as sources of baseline control data and, therefore, comparative baseline studies have been carried out on other relatively unpolluted South West England estuaries; in particular the Erme, Fowey and Avon Estuaries (Figures 1.4, Enclosure 1, b-d). These estuaries receive discharge water from metalliferous mining regions as both naturally weathered products and from mines abandoned at the end of the last century or early part of this century. The data from these estuaries has been used to assess natural and anthropogenic influences because of the absence of pre-impact data for Restronguet Creek. The metals stored in the sediment and the continued drainage from the old workings are also, to some extent, still affecting the contamination levels of these areas.

Figure 1.1: Ariel photograph of the ochre coloured plume of acid mine drainage from Wheal Jane tin mine exiting Restronguet Creek. Photograph courtesy of Channon Photography (1992).

Figure 1.2: View of the Clemows tailings lagoon at Wheal Jane tin mine.

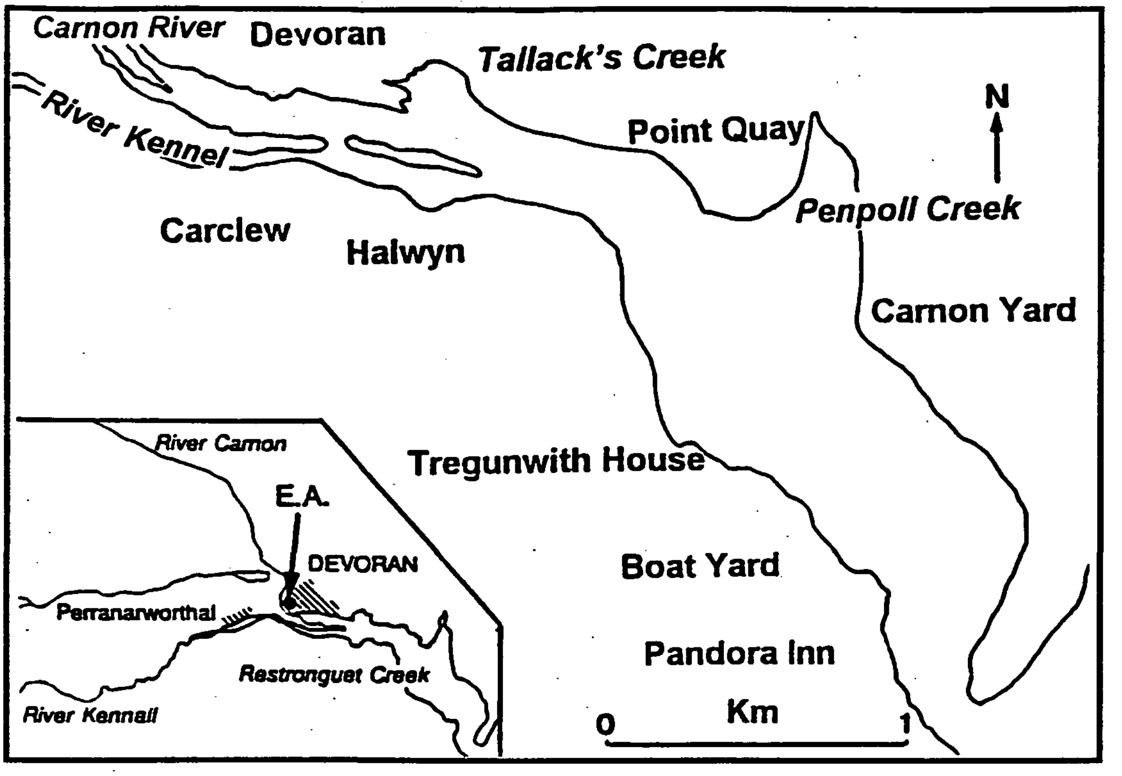


Figure 1.3: Map of Restronguet Creek. The inset map shows the position of the monitoring station (Environment Agency). After Stubbles *et al.,* 1996a.

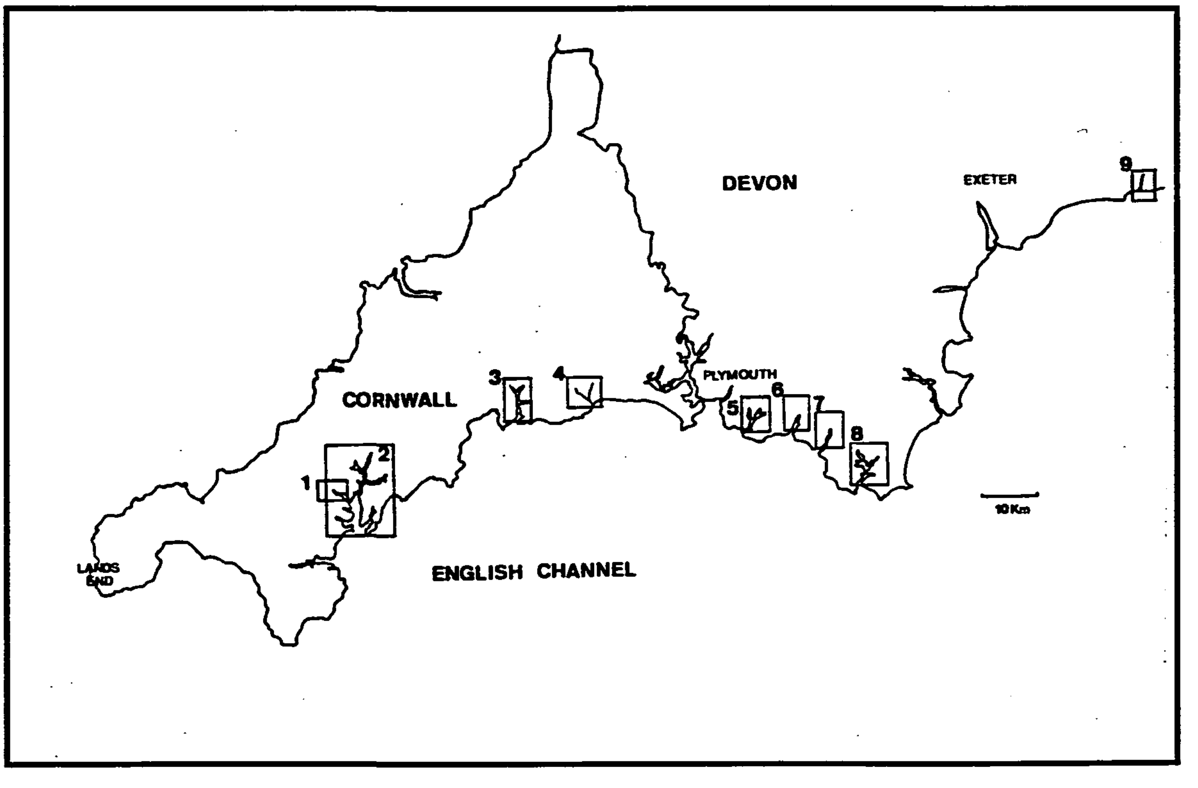


Figure 1.4: Map of SW England. Boxes enclose the estuaries sampled during this study. The numbered boxes represent: 1 = Restronguet Creek, 2= Carrick Roads, 3= Fowey Estuary, 4= Looe Estuary, 5= Yealm Estuary, 6= Erme Estuary, 7= Avon Estuary, 8= Kingsbridge Estuary and 9= Axe Estuary.

1.2 Sampling strategy

As only a few estuaries on the south coast of Devon and Cornwall have been sampled for foraminifera (Section 1.3.1) several estuaries have been investigated for the purpose of providing control data. From this reconnaissance survey, appropriate estuaries were selected (Figure 1.4 and Table 1.1). For the selecton of each estuary the following criteria was used:

- Typical estuarine abiotic variables.
- Typical estuarine species distribution and diversity profiles.
- Have lower concentrations of metals but the drainage catchement should include areas of metalliferous geology.

As a consequence, the Erme, Fowey and Avon estuaries were selected as the control sites which also contribute baseline data on areas not known to have been systematically sample previously.

	1992				1993				1994				1995			
	W	Sp	S	A	W	Sp	S	A	W	Sp	S	A	W	Sp	S	A
RC			R	*	*	*	*	*	*	*	*	*	*	*	*	*
E				R	*	*	*	*								
F									R	*	*	*	*	U		
Av														R	*	*
CR				R		R	R	R				R				
K				R	R	R	R									
L						R										
Y						R										
Ax															R	

Table 1.1: Order of sampling. The abbreviations are: R - reconnaissance sampling, U - samples taken but not analysed, * systematic sampling, grey boxes - no samples taken, RC - Restronguet Creek, E - Erme, F - Fowey, Av - Avon, CR - Carrick Roads, K - Kingsbridge, L - Looe, Y - Yealm and Ax - Axe.

In addition, the environs of Carrick Roads which include the creeks of Percuil, Mylor and Pill, and, the estuarine channel locations in the Truro, Fal and Tressilian rivers (Figure 1.5), were occasionally sampled (Table 1.1, as CR) to identify the geographical distribution of the agglutinating foraminifera in locations adjacent to Restronguet Creek where these species are absent (Chapter Five, Section 5.7).

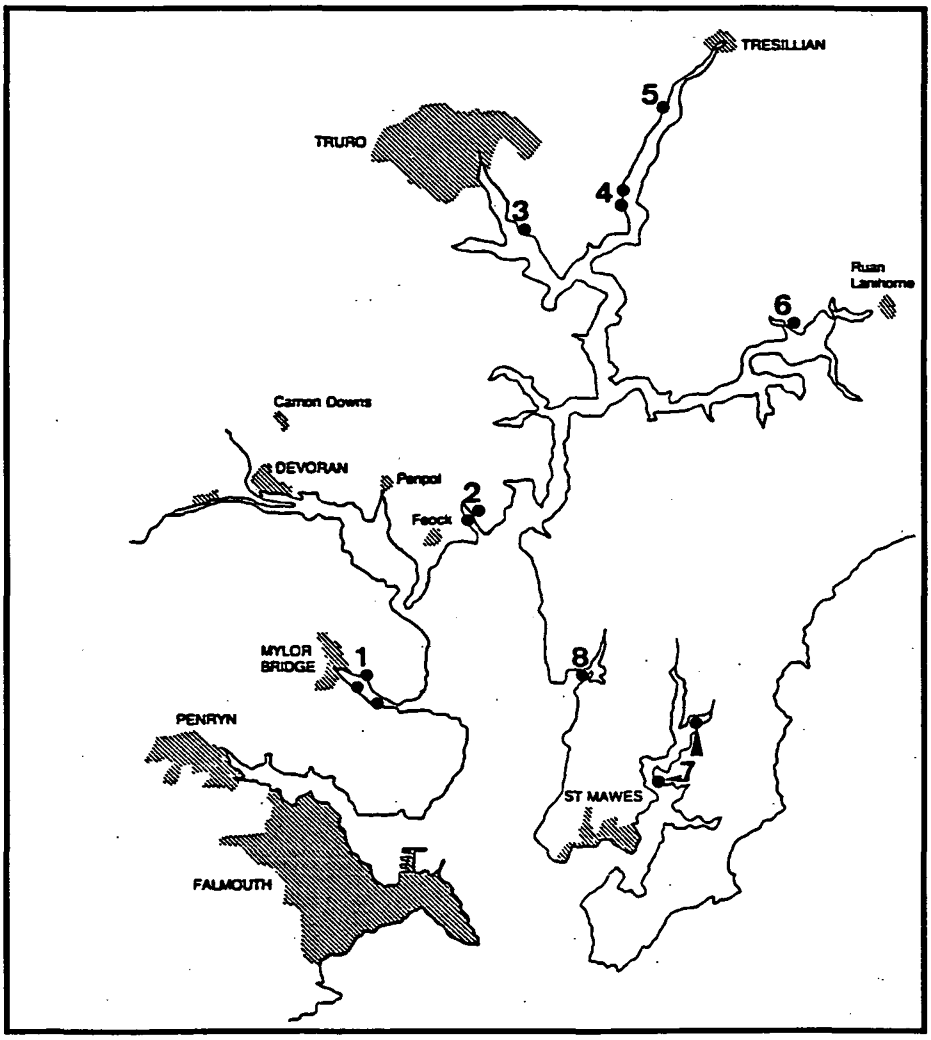


Figure 1.5: Carrick Roads and the additional reconnaissance sample points. 1 = Mylor Creek, 2 = Pill Creek, 3 = Truro River, 4 = St Clements, 5 = Tresillian River, 6 = Ruan Lanihorne, 7 = Percuil Creek, 8 = St Just. The number of samples taken is denoted by the number of dots

Restronguet Creek was sampled between October 1992 (Table 1.1) to the present but sample analysis ceased with completion of the October 1996 data set.

This continuous sampling scheme was designed to determine seasonal and longer term changes in foraminiferal species distribution and test condition.

Significant changes in foraminiferal species distribution, diversity and test condition may be long term responses within a background of long term mining influence (Section 1.5.1) and hence, the sampling period was extended to determine present impact events from historical influence. The need not to deplete and disturb the assemblages in Restronguet Creek more than is absolutely necessary has also to be considered. Material was, therefore, removed every three months rather than monthly (Chapter Five).

1.3 Previous research

1.3.1 Recent estuarine foraminifera of South West England

Foraminiferal research of estuaries in the South West of England has essentially concentrated on species distribution and population dynamics. The earliest work is that of Brady (1870) which describes the distribution of foraminifera and ostracod species from several estuaries and, specifically, the Exe Estuary in which the ecological requirements of brackish water species are described. The early work of Heron-Allen and Earland (1916) describes certain species and their distribution as total assemblages from material dredged from the nearshore regions off the south coast of Cornwall. The later paper of Heron-Allen and Earland (1930) describes species taken from Plymouth Sound and adjacent areas. The material from this collection is held at The Natural History Museum (London) and has been consulted during this research. Many of these early papers are straight forward descriptions of species and their distribution in Plymouth Sound, the Salcombe Estuary (Kingsbridge Estuary) and the shallow shelf sea areas of south-west England (Worth, 1900a,b; 1902; 1904). However, many were carried out without the aid of specific stains such as rose Bengal and, as a result, their value as determinants of foraminiferal ecology is limited. Myers (1943) determined life by natural colour and pseudopodial activity from laboratory cultures of foraminifera and for general collection purposes used a stain (Myers, 1942a). His study of the test morphology of *Elphidium crispum* (Plymouth Sound, Devon) was undertaken in order to determine sexual phases, rates of reproduction and nutrient supply with reference to potential environmental effects. Murray (1965c) carried out the earliest work in the area using rose Bengal stain on samples taken from various South West England estuaries and nearshore locations. The relationship between live and dead foraminiferal assemblages, species distributions and populations with respect to seasonal variation (as relative abundances) are given in Murray (1965c) as a study of Plymouth Sound, Devon. Data are also included from the Tamar Estuary and adjacent to the mouth of the Plym Estuary, with particular reference to sedimentation rates. Murray speculates as to the origin of the small species found in the dead assemblage which may be reworked fauna and may be indicative of sediment accumulation rates. Murray's "Atlas" on Recent foraminifera (1971) gives brief descriptions of the appearance of certain species in South West England and elsewhere in the British Isles. Murray's later work on the Exe Estuary (1980) describes the methods used to collect and analyse estuarine foraminifera. Species descriptions and comments on ecology are also included. Murray's follow-on work on the Exe Estuary (1983) is a study of population dynamics over a period of 30 months as living and dead assemblages. By the use of certain mathematical approaches the changes in production (reproduction, death, immigration and emigration) are modelled to determine patterns in annual standing crop variation. This work emphasises the need to sample over several years in order to gain insights into interannual variation and also that the sampling position may bias environmental inferences at a very localised level. Ellison (1984) describes the foraminifera and meiofauna (ostracods and copepods) in samples taken near St John's Lake on the Tamar Estuary. In this paper he describes a typical low diversity estuarine species assemblage and found that the size of the population varied between the high-water and the low-water regimes and that the latter regime had the highest abundances. More recently, a short study by Castignetti (1996) describes the species distribution of the Plym Estuary which has a typical, low diversity foraminiferal assemblage. Prior to this current research no work had been carried out on foraminifera as indicators of metal pollution in South West England estuaries. My investigations related to this work Stubbles (1993), Stubbles *et al.* (1996a, b), have recently described the effects of heavy metal pollution on foraminiferal assemblages in Restronguet Creek and species distribution in the Erme estuary (Stubbles, 1995). It is evident from field data (Stubbles *et al.*, 1996a, b) that foraminifera respond to water quality, particularly that which has high concentrations of metals such as acid mine drainage.

1.3.2 Pollution and benthic foraminiferal abundance and diversity

The use of benthic foraminifera as indicators of pollution is a relatively new approach and much of the earlier work has concentrated on changes in the fauna when exposed to sewage effluent (Resig, 1960; Watkins, 1961; Bandy *et al.*, 1964a, b; 1965a, b; Seiglie, 1971b). Bandy and co-workers demonstrate an increase in all calcareous species abundance nearest to the outfalls (Laguna Beach and Hyperion outfalls) but Watkins (1961) found an increase in agglutinated species relative to calcareous species (which also developed test deformities) in relative proximity to the Orange County (California, U.S.A.) sewage outfall. The discrepancy between the two sets of results may have been due to the application of different statistical approaches or the chemical composition of the discharged effluents and types of treatment used (Orange County Report no. 21). Watkins (1961) used the Foraminiferal Number (live plus dead) to explain the anomaly but did not include any data on the composition of the effluent. Bandy *et al.* (1964b), however, reported the pH of the primary chlorinated discharge from Laguna beach outfall to be in the range of pH 7.0-7.3, which suggests that dissolution of calcareous fauna is unlikely (Parker and Athearn, 1959; De Rijk, 1995; Stubbles *et al.*, 1996b). Bandy *et al.* (1964b) use only stained individuals and found this method to be more 'diagnostic' than the live/dead ratio. The authors also found there to be a higher abundance of stained individuals in the area of the outfall relative to the adjacent shelf, but that the diversity at the outfall was reduced. At the Los Angeles County outfall, however, Bandy *et al.* (1964a) identified a dead zone within an area influenced by the outfall. In another area affected by the effluent but with a living assemblage, Bandy *et al.* (1964a) identified dissimilar live and dead assemblages. The live assemblage was dominated by hyaline taxa, the dead by arenaceous forms. This suggests that post-mortem dissolution of calcareous tests had taken place.

Under certain circumstances enrichment in agglutinated foraminifera can occur if the calcareous species are removed during postmortem dissolution (Murray, 1991; DeRijk, 1995; Stubbles *et al.*, 1996b). Bates and Spencer (1979) conclude that the species distribution was modified in response to discharges from the Chesapeake-Elizabeth sewage outfall in Los Angeles and that all species abundances varied with distance from the outfall. The authors found that both diversity and the number of stained individuals increased away from the outfall, with a dead or barren zone adjacent to the source. Bates and Spencer (1979) also conclude that the type of effluent probably had a more significant effect upon foraminiferal condition and distribution than the flow rates of the discharge. Nyholm *et al.* (1977) were able to identify distinct zones away from a sewage outfall supporting foraminiferal assemblages and also which species represented a normal assemblage. They also found that the zone nearest to the outfall did not support foraminifera, but was colonised by nematodes, podopleans and the polychaete *Nereis diversicolor.* Bartlett (1972) also identified alteration in calcareous species distribution and that test deformity occurred in response to various sources of pollution; in particular sewage disposal and thermal effluent. Collins *et al.* (1995) conclude that the combination of high organic loading and high river water flow explain the displacement of foraminiferal assemblages and higher abundances of *Ammonia beccarii*, in particular, were present when the organic content was least. Other work on high organic loadings and reduced oxygen concentrations conludes that foraminiferal species distribution, abundance and diversity adversely responded to such impacts (Schafer, 1970; Seiglie, 1971; Schafer *et al.*, 1995). Predation and competition between organisms are considered by Sundelin and Elmgren (1991) to be contributory factors which may affect the susceptability of the foraminifera to pollution. The mesocosm experiments carried out by Alve and Bernhard (1995) established that vertical migration of foraminifera depends upon the oxygen concentrations in the substrate and at the sediment-water interface. The potential loss of habitat due to the effects of pollution, other forms of human disturbance, and global warming have been reviewed by Culver and Buzas (1996) who consider that human disturbance and associated pollution will contribute more to the loss of habitat of both rare and abundant foraminifera than the effects of global warming. Alve

(1995a) reviewed the impact of various forms of pollution on benthic foraminifera and highlighted the problems associated with this work, particularly the dearth of data.

Alve (1991), Alve and Nagy (1986), Ellison *et al.* (1986) and Sharifi *et al.* (1991), have all shown, through field observations, a link exists between heavy metal pollution and foraminiferal response. The research of Sharifi (1991) establishes a link between sediment bound metals (Southampton Water), metal concentrations within the foraminiferal tests and the frequency of test deformity. His culturing experiments also show how premature death and an increase in the proportion of test deformity occurs with an increase in metal availability and accumulation. The cores taken as part of his PhD research (Sharifi, 1991) clearly demonstrate the existence of a pre-contamination period with lower concentrations of heavy metals and fewer deformed tests. The research of Ellison *et al.* (1986) concentrates on species tolerance deduced from core data taken from the Patapsco River and Baltimore Harbour. They conclude that calcareous species are less tolerant of heavy metal pollution and found that the agglutinated species *Ammobaculites crassus* increased in abundance down the core where the zinc concentrations were highest. The converse situation occurs with respect to Vanadium and Chromium which appear to contribute to the decline of *A. crassus*. Similarly, Alve (1991), established a clear connection between metal concentrations in the sediment and species diversity. The cores taken during Alve's study did not, however, extend into an uncontaminated zone to give pre-impact data. Furthermore, Alve (1991) does not provide any insight into the effects of low pH which may have modified the species assemblages preserved. Stouff *et al.* (1999) conclude from their laboratory approach that natural influences (e.g., hypersalinity and acid dissolution) account for high levels of test deformity with similar types of deformation occurring irrespective of the cause.

The experimental effects of low pH conditions on foraminifera have been dealt with by Bradshaw (1961) who found that, for limited periods of time, *Ammonia beccarii* can tolerate acidic water and recalcify, even after complete dissolution of the test had taken place. The effects of low pH conditions on the distribution of calcareous species in the field has been examined by Phlegler and Bradshaw (1966), Schafer (1970) and DeRijk (1995). Phlegler and Bradshaw (1966) note that diurnal variations in pH can restrict colonisation by foraminifera and Schafer (1970) concludes that colonisation by calcareous foraminifera is not established below pH 6.7. Similarly, DeRijk (1995) suggests that the absence of calcareous foraminifera is due to the low pH of the saltmarsh habitats she was studying, the acidic conditions being a natural phenonomon brought about by decomposition of organic matter and bacterial activity. The anthropogenically induced corrosion of foraminiferal tests as a result of exposure to acidified industrial effluent has been reported by Rao and Rao (1979), Setty and Nigam (1983), Rao *et al.* (1985) and Banerji (1990). Setty and Nigam (1984) find that nearest to an industrial outfall which released acidified effluent, there is a barren zone beyond which is an area with a relatively large abundance of agglutinated foraminifera, although those species with test material held together by calcareous cement may show signs of dissolution (Alve and Murray, 1995b). The authors also note a thinning of the calcareous tests, with enhanced rates of test dissolution. Stubbles *et al.* (1996a, b) describe the physical effects of acid mine drainage on foraminiferal tests, which produced wall thinning and layering. The potential for statistical bias with respect to the relative proportion of stained tests, was also noted to be a possibility following postmortem test dissolution.

More recently a new form of pollution and its effect on foraminifera has been identified by Hallock *et al.* (1995). The authors suggest that the disease affecting foraminifera living off the Florida Keys, noted to be very clear, non-turbid water (M.B.Hart, pers. comm., 1998) is the result of irradiance (exposure to high levels of ultra-violet light). The review by Alve (1995a) has summarised the many other forms of contamination; for example the discharge of paper and wood pulp and hydrocarbons (Vérec-Peyré, 1984) and the adverse effect these have upon foraminiferal assemblages and test condition. Coull and Chandler (1992) report that foraminifera are not adversely affected by crude fuel oils, but that their abundance increases. Oil dispersants, on the other hand, have an adverse affect on the foraminiferal assemblages.

1.3.3 Geochemical analysis and other organisms - South West England

Restronguet Creek has been investigated with respect to the concentration of heavy metals stored in the sediment and their bioavailability. The baseline control estuaries have been investigated to provide background metal concentrations. The concentration of certain sediment bound metals in the Fal Estuary and, in particular, in Restronguet Creek, has been shown by previous research to be abnormally high (Hoskings and Obial, 1966; Yim, 1972). Hydraulic Tin Ltd. were working the tailings waste at Wheal Jane for cassiterite and sulphide ores in 1958 and analysis of the mill float showed relatively high concentrations of certain metals, in particular Cu, Fe and S (Hosking and Obial, 1966) which suggests that mine water waste stored in the lagoon was a reasonably efficient way of removing metals. There appeared to be no change in the metal concentrations in Restronguet Creek in the interval (1966-1972) between the two periods of research which coincided with a period of inactivity at the Wheal Jane mine. Yim (1972) did, however, note the presence of fresh metal ore in sediments which originated from the preparatory work undertaken in 1971 just prior to the re-opening of the mine in 1972. These early studies concentrated on total analysis of sediments rather than on what may be easily available to an organism (bioavailable). The most comprehensive study of bioavailable and bioaccumulated metals is the review by Bryan and Langstone (1992) of sedimentary metal concentrations and metals accumulated in macro- and meio-fauna and aquatic flora in several estuaries of the UK, including Restronguet Creek and the Fowey, Erme and Avon Estuaries. The highest concentrations of As, Cu, Ni, and Zn occurred in Restronguet Creek and probably accounted for the absence of several species of bivalve and the overall low diversity (Bryan and Langston, 1992; Sommerfield *et al.*, 1994a, b). The highest levels of Cd and Pb were found in sediments taken from the Gannel on the north Cornwall coast. The Avon provides some of the lowest concentrations of metals in the region and has frequently been used as a control site. Restronguet Creek formed part of a study carried out by Thornton *et al.* (1975) which investigated the effects of heavy metals on oysters. As Restronguet Creek is a holding rather than a rearing area for oysters the animals were not analysed for metal accumulation but the sediments were found to have high concentrations of heavy metals compared to the other areas. The other areas studied did show that the metal concentration within the sediments and water was positively correlated with the concentration of metals in the oysters.

Work on the effect of different metals on polychaetes (e.g., *Nereis diversicolor*) has been reported by a number of authors. Bryan and Hummerstone (1971) detected a positive correlation coefficient association between copper concentration in the sediments and the concentration in *N.diversicolor* in Restronguet Creek and the Avon Estuary. Furthermore, high sedimentary Cu concentrations caused high uptake by the organism, particularly by those polychaetes introduced into Restronguet Creek from areas with low metal concentrations. This conclusion was supported by the LC_{50} experiments carried out by the authors which show that Restronguet Creek is inhabited by populations of *N.diversicolor* resistant to Cu pollution. The cross colonisation work carried out by Bryan and Hummerstone (1971) agrees with the work of McNeilly and Bradshaw (1968) who also found that organisms (terrestrial plants) transferred from non-contaminated sites to contaminated sites were intolerant of heavy metals which suggests adaptation exists within the same species. The adaptation of *N.diversicolor* to elevated Zn concentrations, as well as Cu contamination, has also been investigated by Bryan (1974). The highest Cu concentrations in both the sediment and the polychaete occurred in samples taken from Restronguet Creek with the same species containing 1.76 ppm more Cu than those taken from the Avon Estuary. However, there was little difference in the concentration of Zn within the organism either from Restronguet Creek or from the Avon control site. Bryan and Hummerstone (1973b) conclude from this earlier work that the organism is able to regulate Zn. In the Looe Estuary the metals Pb and Ag show concentrations in the sediment which are proportional to that within the organism, but adaptation is only found for Ag (Bryan and Hummerstone, 1977). Adaptation to As is not found, and Cd was not found to be toxic to *N.diversicolor* (Bryan and Hummerstone, 1973b).

The work of Somerfield *et al.* (1994a, b) studied the effects of certain metals, in particular Cu, on nematode and copepod communities in the Fal estuary system. Somerfield *et al.* (1994a) conclude that certain species of nematode have developed tolerance mechanisms to metal contamination but that the sediment dwelling (endobenthic) copepod species had not, as they were absent in Restronguet Creek but present in the other creeks forming the Fal estuary system. The authors highlighted the chemical variability of the sediment and interstitial water which can be caused by the interaction of a number of parameters, for example, organic carbon content, temperature, competition between metals and preferential binding between metals and Fe oxides. Somerfield *et al.* (1994b) and Williams *et al.* (1998) detected no increase in sediment metal concentrations after the discharge in 1991 compared with results obtained previously. The low pH of the mine discharge (pH 4.65-5.75) was considered by the authors to account for this, whereby metals would be kept in solution above the higher saline tidal water and transported out into the Carrick Roads where precipitation would take place. The authors conclude that the County Adit (Section 1.5.1) remained a major source of contaminated water, in addition to that emanating from Wheal Jane. Nonmetric multivariant analysis has been carried out on biotic and geochemical data obtained for Restronguet Creek and the Fal Estuary by Clarke (1999) which demonstrates the spatial distinctivness of these locations relative to other regions in south - west England.

Fucoid algae were also investigated by Bryan and Hummerstone (1973a) using material collected from Restronguet Creek and the Tamar, Camel and Dart Estuaries. The specimens taken from Restronguet Creek show a horizontal gradient trend in Cu, Mn, Fe, Pb and Zn, with the highest concentrations nearest to the source. Concentrations of Cu and Zn are highest in material taken from Restronguet Creek, relative to the other estuaries under investigation, but the Tamar material shows the highest concentrations of Mn, Fe and Pb. Analysis of the sediment, however, shows that the highest concentrations for all the metals analysed are found in Restronguet Creek, suggesting that uptake of Mn, Fe and Pb could be regulated by these algae. There was also a gradient of metal concentration within the fucus itself, with the highest values derived from the older parts of the thallus.

1.4 Overview of the geology and mineralisation of Devon and Cornwall

The mineralisation of the South West of England is the product of the Variscan Orogeny with the Devonian (the oldest being Emsian in age, c.390 Ma) and Carboniferous strata being intruded by the Cornubian Batholith (Figure 1.6). The granite bodies are exposed as either large plutons (Dartmoor, Bodmin Moor, St Austell, Carnmenelis and Lands End) or as small cupolas in between the larger bodies. All form an ENE-WSW trend and extend for approximately 300 km from the Haig Fras in the far west to the eastern margins of Dartmoor (Alderton, 1993).

The Devonian sedimentary rocks are a mixture of carbonates, mudstones, siltstones and sandstones metamorphosed to greenschist facies to form pellites and psammites. These Devonian units comprise the oldest rocks in the area and were formed in a marginal marine environment approximately 390 million years ago. They are interspersed with Carboniferous limestones, siltstones and mudstones which have also been subjected to low grade metamorphism. The intrusion of the granites formed a thermal metamorphic aureole within the country rocks (killas) and a gradient of low grade metamorphism extends away from the focus of thermal contact. The Start Point and Lizard complexes (Figure 1.6) provide examples of higher grades of metamorphism. The Lizard complex is considered to be formed of Precambrian muds, sandstones and basaltic lavas, ultimately metamorphosed to hornblende-schists (Edmunds *et al,* 1975).

After faulting and alteration of the schists, a series of intrusions developed consisting of acid sills, basic dykes and peridotite which is now altered to serpentinite (Edmunds *et al.,* 1975). The Plymouth Limestone of Middle Devonian age can be found in the immediate vicinity of Plymouth, with good exposures to be found on the Hoe as well as elsewhere. To the east are found Permian and Mesozoic sediments that are largely free of metalliferous veins but which provide the only water aquifer in Devon and Cornwall. These Mesozoic sediments once covered the entire area, including the granite batholith but which were eroded in stages to leave the small areas of Cretaceous and Jurassic (and possibly Triassic) strata in the east of Devon.

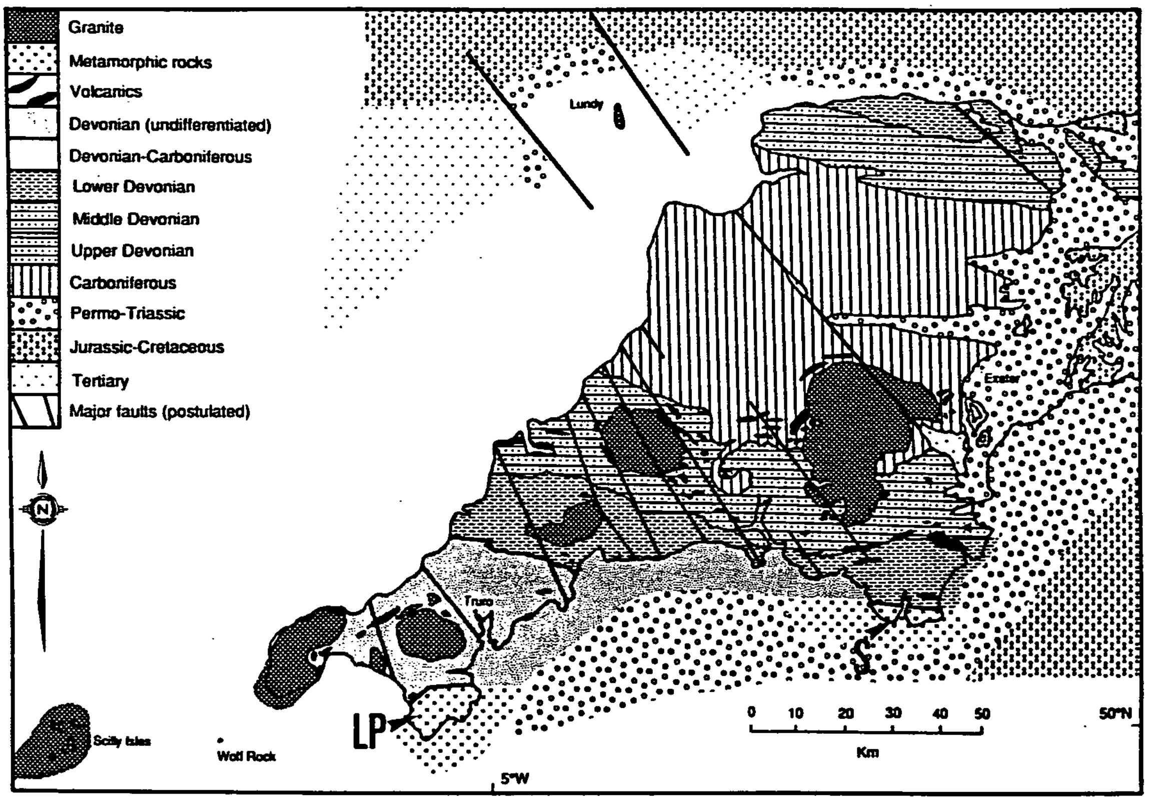


Figure 1.6: Regional geology of SW England. After Alderton, 1993.

In more recent times the geology and geomorphology of South West England has undergone modifications which have contributed to its present day appearance. The primary influence was the repeated incursion of the ice sheets which only reached the northern coast (as it is today) but which had repercussions for the area immediately to the south. Interspersed periods of periglacial activity produced episodic erosion which removed significant amounts of material from Dartmoor, etc., and which infilled the lowland and river valleys. Much of this eroded material formed the alluvial tin deposits which were streamed for by early inhabitants. The coastline extended beyond the present day boundaries and following the last retreat of the ice sheet a marine transgression (between 10,000 and 15,000 years ago) submerged these former coastlines and flooded the river valleys (Clarke, 1970). This latter process produced the rias which typify the region. Continued erosion has ensured the exposure of the granites and surrounding older strata (which contain the metalliferous veins) to accessible levels for metal mining, china clay extraction and further physical and chemical weathering (Keller, 1955; Fookes *et al.*, 1971). Alteration of the granites has produced areas rich in kaolinite with veins of quartz, fluorspar and tourmaline, which are particularly associated with the St Austell granite and the Fowey River catchment.

The mining region of South West England has been described as "one of the greatest mining districts in the World" (Alderton, 1993). This metalliferous region is polymetallic but is better known for copper and tin extraction (Section 1.5) with an estimated total tonnage of 2.5×10^6 of tin and 2×10^6 of copper extracted. Most of the mineralisation of South West England is related to the granites as either pre-, syn- or post-intrusion. Native copper and some sulphide mineral formation is mid-Devonian to early Carboniferous in age and pre-dates the granite intrusion (270 - 300 Ma). The main cassiterite (tin oxide) mineralisation occurs in quartz veins, with some sulphide formation, and is the result of early to mainstage mineralisation. The early mineralisation (270 - 285 Ma) resulted in porphyry stocks and greisens, but the mainstage episode formed mineral veins (lodes) in the granite aureole rocks as swarms, fissure veins, stockworks, pipes and floors (Collins, 1882). The lead-bearing mineral galena and sphalerite (zinc oxide), with other sulphide mineral formation, post dates the intrusion and is Permo-Triassic in age, possibly Triassic (Alderton, 1993).

The mineral deposits occur in distinct zones around the granite. Tin and tungsten are more abundant in the inner zone, with copper, zinc and iron formed further away. Lead is not found within the granite bodies but only in the adjacent country rocks. This mineral becomes progressively more dominant in east Cornwall/west Devon (Edmunds *et al.,* 1975) which is why the mines further east extracted only silver-lead (Section 1.5.1). Magnetite mineralisation probably formed from volcanic rocks rather than by hydrothermal processes. The evident mineral zonation corresponds to a temperature gradient, brought about by a temporal and spatial decrease in the hydrothermal fluid intrusions. The temperature for tin mineralisation is 300-400°C, whereas for lead, zinc and iron it is 150°C. The hydrothermal fluids probably originated from the surrounding sediments and by convective currents (thought to have existed at the time) the metals were leached from the sediments and the granite to be concentrated within the mineral zones. The contraction cooling joints and fractures in the granite would have enabled the fluids to enter the granite body and scavenge additional metals.

Wheal Jane and the other mines within the Carnon catchment were polymetalic but the primary products were tin with some copper, zinc, lead, arsenic and silver. Further east, within the Fowey catchment the mineralisation was less diverse but the mines also extracted tin and copper with some iron and lead. Further east still, the Tavistock mining area produced mainly copper, lead and arsenic. Finally, the Avon and Erme mining areas were noted for silver-lead mining; tin extraction was mostly by surface raking and alluvial streaming. It is apparent that metal abundance and variety decreased from west to east.

1.5 Metal mining activity

1.5.1 Past metal mining - Devon and Cornwall

Edmonds (1868) reviewed the Phœnician tin trade in Cornwall. These sea traders, originating from the Middle East, were thought to be trading for tin in the Cornwall area by 375 B.C., however, Hatcher (1973) considered this to be unlikely. The technique of smelting may have originated in the Middle East as many ancient furnaces have been discovered in Cornwall and were called "Jew's-houses" (Henwood, 1843). The presence of smelters with associated trade routes suggests that ore was eventually imported and smelted from other mining areas, thus increasing the potential for contamination.

The Stannary Charter of 1201 is the first record of tin mining in Cornwall (Worth, 1874) and indicates the existence of a settled and well established mining industry. Taylor (1800), however, states that few mines between the Norman invasion and the end of King John's reign were profitable and those that were, had been mostly managed by Jews who were aquainted with the technology required and had the investment potential necessary for improved productivity and the refinement of low grade ore rock. Extraction rates declined because of the banishment of the Jews by Edward I in 1290. The mines were, therefore, left unworked as metal refining was a technology unknown to the miners and there was no market for unpurified tin, known as 'black tin' (Taylor, 1800). Various primary historical sources refer to copper extraction in the reigns of Henry VIII and Edward VI as not being extensive which resulted in productivity not satisfying home demand and consequently export was prohibited (Collins, 1895; Maclean, 1874). In addition, most copper extraction before 1700 was carried-out while mining for tin and then only at shallow levels (Collins, 1895). An improvement in metal extraction techniques had occurred by the reign of Elizabeth I (Maclean, 1874) and the geographical areas affected by mining had been extended from alluvial workings to deep lode working. There was also a change in productivity at about this time, with a decrease in the east of Cornwall but an increase in the west (Maclean,1874). The quantity of tin coined (a method of assay [Barton, 1967]) at Truro in 1305 was 153,843 and in 1607 the figure rose to 426,492 (values in pounds weight). For Liskeard, in the east of the county, however, the figure declined from 79,160 in 1577 to 35,010 in 1607 (Maclean, 1874).

Based upon his interpretation of Carew's work written at the end of the 16th century, Collins (1895) determined that underground tin mining to a depth of more than 50 fathoms (91 metres) was developed in the 15th century. Deep mining is known to have occurred at a few mines in the early 18th century; e.g., Poldice in Gwennap in 1733. The invention and use of pumping machinery facilitated the mining of lodes at greater depths and increased the number of workings. Wheal Virgin lode, for example, was discovered in 1757 and pumping allowed the systematic extraction of copper (Collins, 1895). By the beginning of the 19th century there were 45 mines worked solely for copper, 18 for copper and tin, one for silver and copper and one for copper and cobalt (Collins, 1895).

Mining was at its zenith at about 1855, and by 1869, 84 mines were recorded in Cornwall. The decline began about 1870 with a gradual reduction in the number of working mines and ore productivity so that, by 1885, only 35 mines were active (Collins, 1895). According to estimates made by Collins (1895) the Gwennap mines alone had sunk, and driven through, 265 miles of ground.

The decline was due primarily to the expense of working the more inaccessible lodes (Hill and MacAllister, 1906) and the high cost of pumping as Cornish mines are the wettest in the world (pers. comm. Carnon Holdings, 1992). The import of more easily won ores from Brazil and other countries caused the price to fall and home produced ore could not compete. During periods of high prices mines were re-opened but soon closed when the price fell (Barton, 1967). Small operators, called tributers, continued to work mines which did not require extensive operational technology.

***i*) Carnon Valley**

Figure 1.7 shows the areas of deep mining activity in the Carnon Valley catchment, but the first occurrence of working these subsurface mines is impossible to determine. Ting Tang, for example, is regarded by Stephens (1940) to be the oldest in the South Gwennap area, but the first record of its performance is 1816 (Collins, 1912). Many more are in isolated locations in the South Gwennap area and these are considered by Stephens (1940) to be very ancient.

As with other mining districts in south - west Cornwall the metals extracted were wide ranging in type, including native silver (Collins, 1892; 1904) but only the most easily obtained were mined in the early part of the 17th century (Collins, 1873). When mining began in the Carnon Valley is unclear but initially, as elsewhere in the county, surface mining and streaming were the early methods used (Barton, 1967). Many of the above mentioned "Jew's-houses" were situated adjacent to stream work locations and in the parish of Kea (including the Carnon Valley) a Jew's house has been found (Henwood, 1843). Worth (1874) and Collins (1881) mention the presence of numerous artefacts used to work tin, in particular a deerhorn fashioned into a pick was found in Restronguet Creek in

1801 and dated between 4000 and 6000 B.P.

The partially collapsed County Adit (Figure 1.8) forms a drainage channel into the river just north of Bissoe and remains in use. This engineering venture was begun in 1748 and completed in 1790 allowing the efficient removal of mine waste water (Henwood, 1843; Stephens, 1940). The adit connected the mines in the St Day, Gwennap and Wendron areas (Henwood, 1843) with some branches extending to 48.3 km in length (Hosking *et al.,* 1966). Until 1854 water enriched in Cu was discharged into the Carnon River via. the County Adit but following the introduction of precipitation pits along the Carnon River water entering Restronguet Creek was greatly improved (Hamilton-Jenkin, 1963).

In Restronguet Creek, detrital tin mining took place from 1822 to 1845 (Dines, 1956). Two relatively large stream mines were active in the 18th and 19th centuries; the Carnon Stream Mine and the Carnon Yard Mine (Figure 1.7). Prior to this, in 1800, some deposits were worked but flooding caused the extractions to be halted (Henwood, 1843). In 1871 the Restronguet Creek Tin Stream Works commenced exploitation of the remaining reserves (Taylor, 1873). Initially the venture was profitable, but the mine became uneconomic by 1873 and in 1879 the equipment was auctioned (Simpson, 1990).

Although in the later years the mines were worked only intermittently when tin prices were high, tributers again operated whenever other work was not available and the area was seldom left unworked for very long periods (Dines, 1956). The boom periods, however, were times of major disturbance (Barton, 1967). Wheal Jane (see Section 1.5.2) was the last mine to be active, closing in 1991.

Past associated commercial activities have included boat yards at Devoran and, while in existence, the depth of water was retained by various methods to remove the build up of silt. A sluice gate mechanism was in operation, for example, at the road bridge near Devoran which acted as a dam and after each incoming tide brought in sediment it was flushed away into Carrick Roads by the dammed channel water (Simpson, 1990). This was carried out during the most extensive and productive mining period in the area and thus, the uppermost part of the sediment column in Restronguet Creek is not a continuous, undisturbed time record.

In addition to pollution directly attributable to mining, the associated smelting works at Penpoll and Bissoe also produced contaminants and atmospherically transported material was distributed over a wide area. Arsenic recovery at the Bissoe Arsenic Works was well established by 1800 (Dewey, 1920), with the import of material for arsenic purification in addition to locally produced material. Bissoe also became an established national centre for arsenic recovery (Hamilton-Jenkin, 1963). After the closure of the smelters near Truro all refining operations were transferred to Penpoll, thus increasing atmospheric output and hence pollution in this century. While in operation the only bulk transport route to and from the smelters, particularly before the railway was in use, was by barge via. Restronguet Creek.

Various other foundries, smelting works, chemical works and a gunpowder factory were in operation in the 18th and 19th centuries within very short distances of the Creek. The area did not, therefore, benefit from extensive periods of non-commercial activity and as a consequence the levels of pollution have always been high.

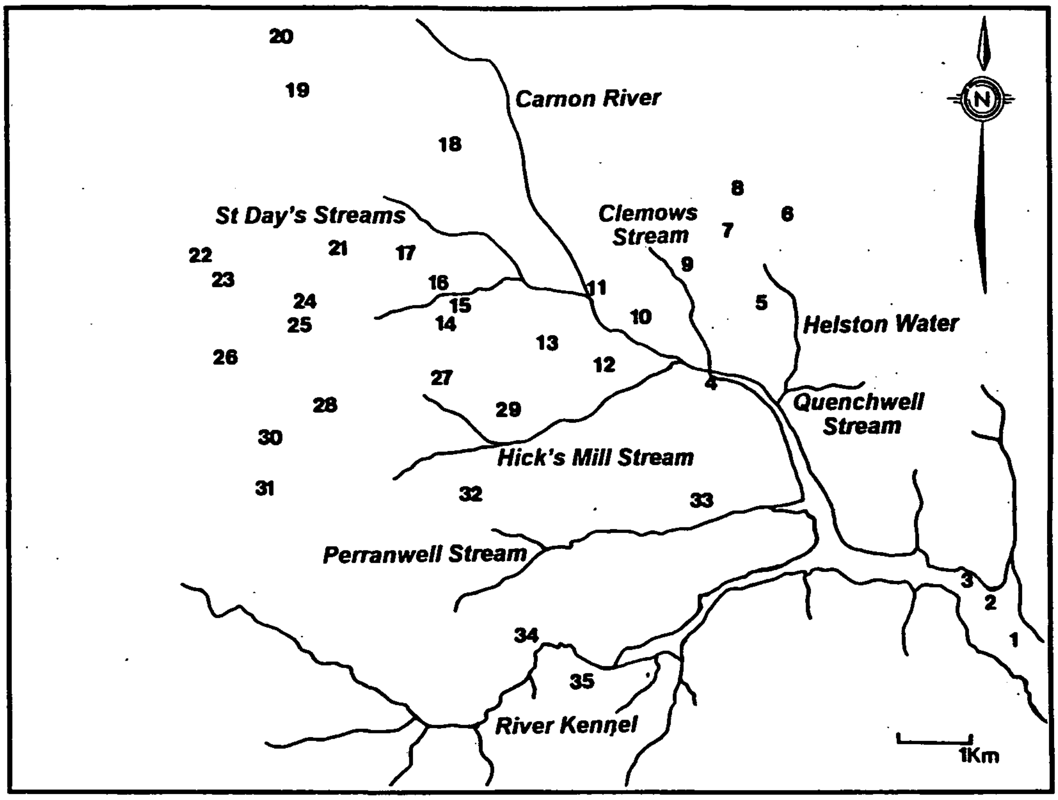


Figure 1.7: Map of the mines and river system within the Carnon Valley. The numbered sites represent the more productive mines:

1 Carnon Yard Stream Works, **2** Restronguet Stream Tin works, **3** Upper Old Works, **4** Bissoe, **5** Great Wheal Badden, **6** <u>**Wheal Jane**</u>, **7** Wheal Sperris, **8** Falmouth, **9** Wheal Hope, **10** Nangiles, **11** Twelveheads, **12** Wheal Friendship and Wheal Clifford, **13** Mount Wellington, **14** Wheal Lovelace, **15** Wheal Fortune, **16** Wheal Maid, **17** Poldice, **18** Chacewater, **19** Halbeagle, **20** Scorria Mine, **21** St. Day, **22** Wheal Gorland, **23** Roslabby, **24** Wheal Jewel, **25** Wheal Virgin, **26** Wheal Damsel, **27** United, **28** Wheal Squire, **29** Ale and Cakes, **30** Ting Tang, **31** Pensruthal mine, **32** Gwennap, **33** Silver Hill, **34** Tresavean, **35** Wheal Magdalen.

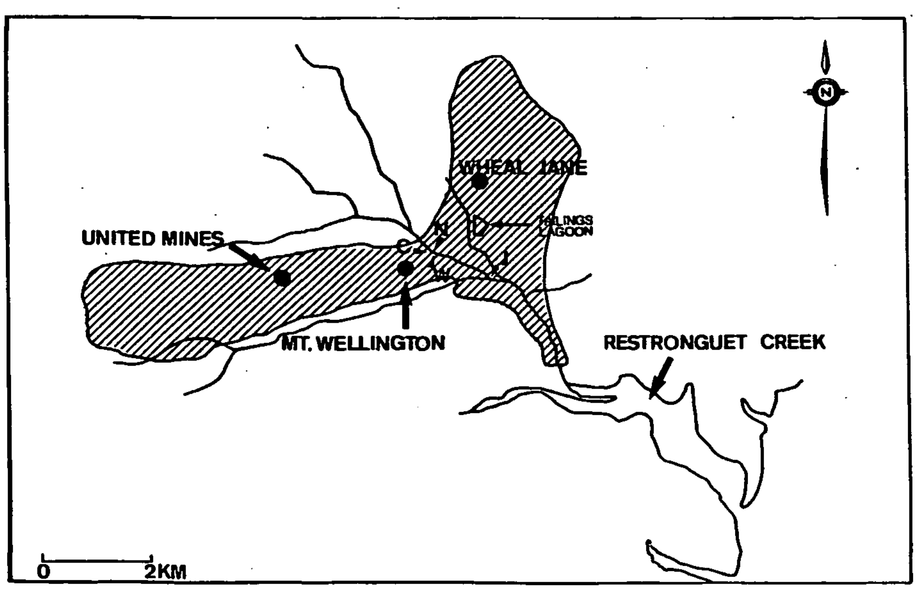


Figure 1.8: Mine drainage catchment and adits. Featuring Wheal Jane, Mount Wellington and the adits, County (C), Nangiles (N), Wellington (W) and Jane (J).

***ii*) The River Erme valley**

There are several sites within the catchement of the Erme which were actively mined for silver-lead but overall the area was not very productive. As with other sites containing winable metal the area was streamed for tin and other metals (Hamilton-Jenkin, 1974).

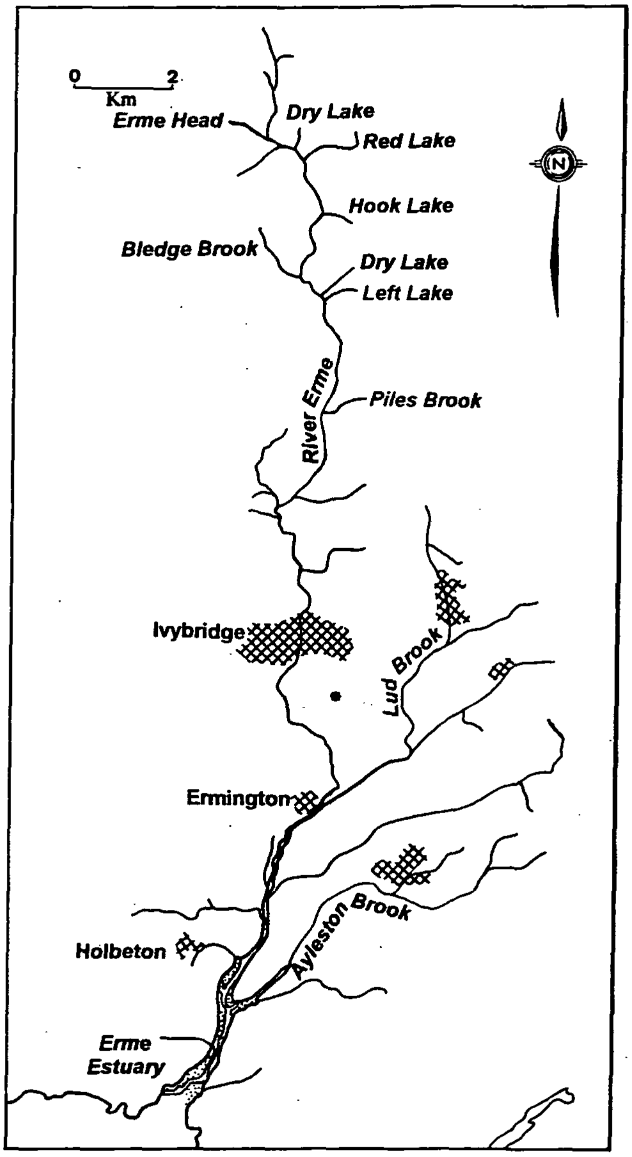


Figure 1.9: Drainage catchment and the location of old mines in the Erme River Valley. The * marks the sites of Filham and Caton mines.

Figure 1.9 shows only the position of the confirmed sites at Filham (Ivybridge Consols) and Caton which worked from the early 19th century to the final quarter of that century (Dewey, 1921; Dines, 1956; Hamilton-Jenkin, 1974). In addition, there are a number of unconfirmed sites which appear to be ruins of blowing houses and other related artefacts in the upper reaches of the Erme where surface working for tin took place (Butler, 1992). Copper extraction is unrecorded for the Erme valley (and also for the Avon) and this reflects the progresive change in the type of ore available, between the west of Cornwall and Devon (Dewey, 1923).

***iii)*The River Fowey valley**

The position of mines affecting the catchment of the Lerryn River and the Fowey River and it's tributaries Cardigan Water, St Neot and Warleggan, are shown in Figure 1.10. The area was not, however, as productive as areas further west (Maclean, 1874; Hamilton-Jenkin, 1967). The Pb mines were generally placed to the south of the granite margins within the country rock, while Sn extraction (as cassiterite) took place within the granite itself. Wheal Howell was one of the largest mines, but there is no reference to it before 1832. Trevaddoe was also a large mine and reported gains began in the 18th century, with Cu extraction taking place from 1823 to 1911. During the latter part of the 19th century and into this century, Treveddoe was mostly an opencast mine for black tin. In 1943 the mill was rebuilt and used to recover metals from the tailings, and at the time of Dines (1956) going to press the mine was still being worked but with no recorded returns (Burt *et al.*, 1987). East Wheal Rashleigh was worked from 1821-1874 for Cu, Mn, Ag and Fe but was probably in production well before that time. The few mines that were working into this century (Burt *et al.*, 1987) were, Pelynwood (Sn), St Neot, Hobbs Hill, Tregeagle (Sn), Hurstock (Pb), Bodithiel (Pb), Kilham (Sn), Gazeland (W) and Restormel Royal (Fe).

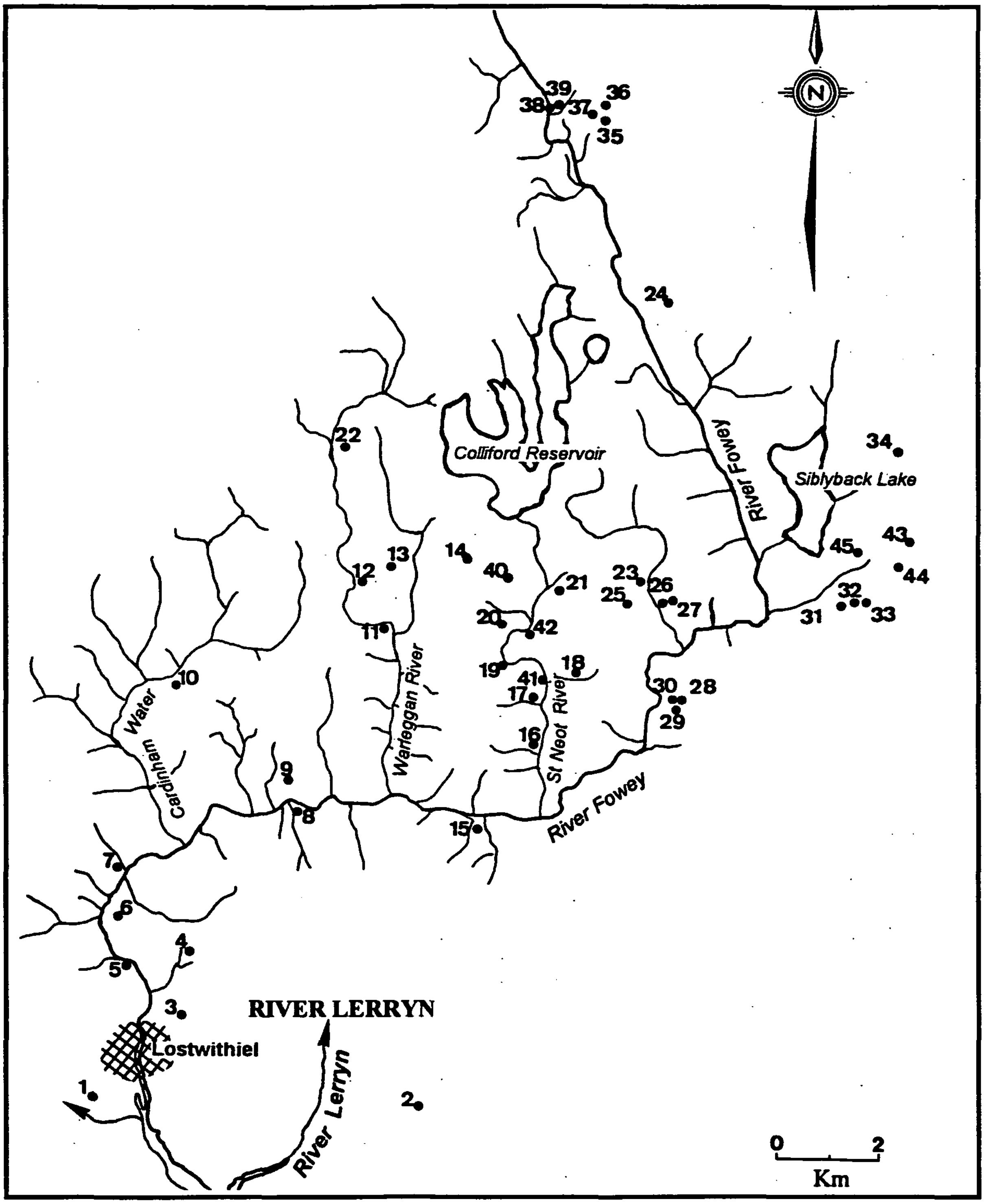


Figure 1.10: Map of the Fowey River mining district. The numbered sites of the better known mines are:

1 Pelynwood, **2** East Wheal Rashleigh, **3** Beacon Hill, **4** Fortescue North, **5** Duke of Cornwall, **6** Restormel Iron, **7** Respryn, **8** Sicily, **9** Jane East, **10** Glyn, **11** Carn Vivian, **12** Trevaddoe, **13** Whisper, **14** Gazeland, **15** Bodithiel, **16** St Neot or Trevenna, **17** Mary Great Consols, **18** Ambrose Lake, **19** Gooneva, **20** Tregeagle, **21** Hardhead, **22** Hobbs Hill, **23** Goodsver, **24** North Wood, **26** Bowden, **27** Carpuan, **28** Kilham, **29** Tamworth, **30** Coryton, **31** Penhale and Larkholes, **32** Caradon West South, **33** Norris, **34** Phoenix Wes, **35** Jane, **36** Cannaframe, **37** Worthy, **38** Treselan and Scaddick, **39** Tresellyn, **40** Hammet Consols, **41** Tin Valley, **42** Robins, **43** Craddock Moor, **44** Caradon Consols, **45** Pollard.

Within the Fowey River catchment there was one smelter at Lostwithiel but by 1805 was not in use (Barton, 1967) as nearly all metal production had transferred to the smelters at Truro and Penpoll (on Restronguet Creek) where the bulk of the metal ore was mined. Of the three control sites, mining and ore production in the River Fowey catchment was the largest.

iv) The River Avon valley

There were few mines affecting the Avon catchment and those that did exist are not well documented. The most noteworthy is Huntingdon (Figure 1.11), which was worked for silver-lead (as galena) before it was abandoned in 1868.

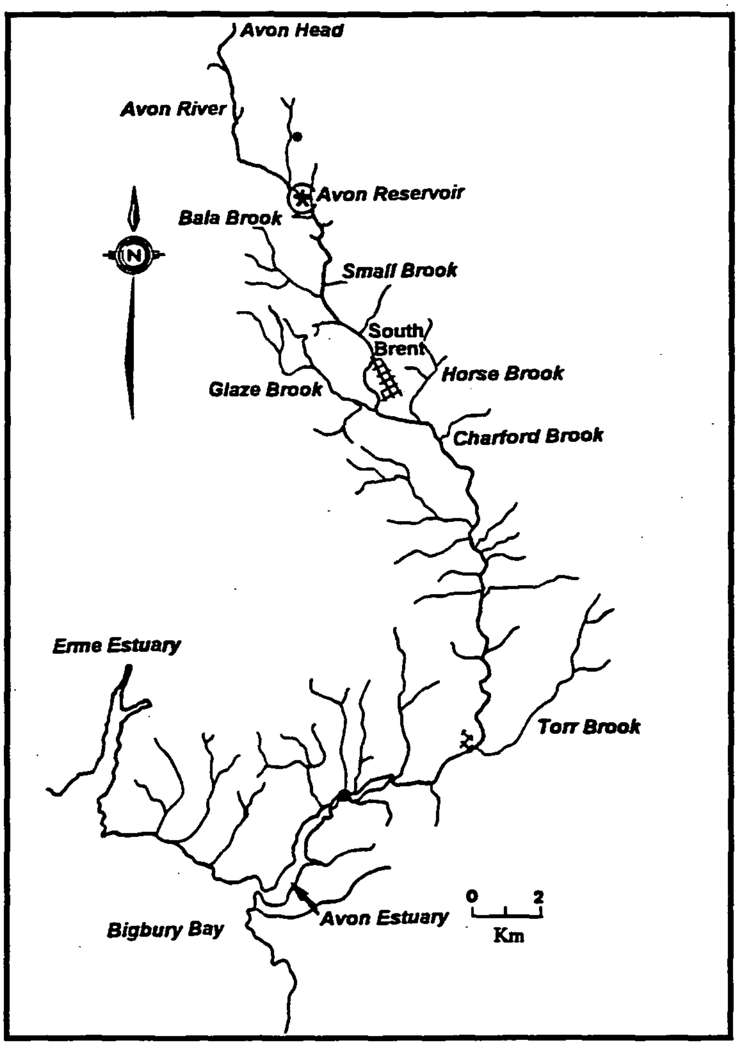


Figure 1.11: Drainage catchment and location of the old mines in the Avon River. The * marks the site of Huntington.

The actual whereabouts and working period of the Wheal Dorothy tin mine, near Heng Lake, is unknown but the fact that it has been documented does indicate that it was a large and economically successful venture. In addition, there were several stream works, many of which have since been submerged by the Avon reservoir. However the waste piles resulting from the Wella Brook stream works at Ryder's Hill are still evident (Butler, 1993). Compared with the mining district of the Erme, ore production in the River Avon catchment was very small.

1.5.2 The Wheal Jane incident and recent mining history

The Wheal Jane incident (Figure 1.1) involved a major discharge of acidic metal-rich mine water which entered Clemows Stream via Nangiles adit (Figures 1.7 and 1.8) in January 1992, following an unusual sequence of events which followed closure of the modern Wheal Jane tin mine in February 1991. Water recharge levels had always been high and pumping had been a major expense for the owners. However, following closure, the pumps were removed and sold allowing water levels to rise. The previously exposed, oxidised and decayed sulphide minerals were mobilised by the rising water, to free metal ions and H_2SO_4 in solution (Cambridge, 1995). This is a typical outcome with respect to mines that were once worked for sulphide minerals (Milam and Farris, 1998). Some discolouration of water flowing from the mine was noted in October 1991 and the Environment Agency (then the NRA) installed their own pumps and began to monitor the situation. The mine owners, Carnon Holdings, devised an S shaped lagoon which proved to be under-designed and could not accommodate the volume of mine drainage and settled-out sludge. The older, but larger, tailings lagoon (Figure 1.2) used by the metal processing plant was used, instead, to store drainage water from the mine. Unfortunately, rainfall was particularly high in January, 1992 and the shafts filled-up more rapidly than predicted. In addition, pumping from behind Jane Adit had to cease due to the high winds. The water backed-up and a localised water pressure conduit to a previously unlocated adit, Nangiles, burst and several million litres of contaminated water were released into the river (Cambridge 1995). It is likely that the new workings (>1972) exposed fresh sulphide minerals and this may account for the high metal concentrations during this discharge relative to previous periods of inactivity.

The pH and concentration of metals in the water before, during and after the incident, are given in Chapter Four. The remedial, but temporary, action taken by the E.A. (Environment Agency) included liming, addition of a flocculating agent and primary settlement in the tailings lagoon. This increased pH removed some of the metals to form a sludge enriched with metals. A pilot scheme using a passive treatment method was inaugurated in 1994 (Cambridge, 1995). This scheme constitutes an open field laboratory and does not make a significant contribution towards improving bulk mine water quality (<1%). The water released from this treatment is pumped back up to the mine area for further lime treatment and settlement in the tailings lagoon. It is illegal to discharge water into the river catchment unless it has undergone treatment by the traditional methods of the addition of lime, flocculating agent and followed by primary settlement (Cambridge, 1995). Hence, the water from the passive treatment plant is returned for primary treatment in the event that the metal levels may be above the designated environmental quality standard (EQS).

During periods of heavy rainfall, high rates of recharge cause untreated mine water being discharged directly into the river at Nangiles Adit. This usually ocurrs in the winter following re-immersion of the working faces, exposed during the summer when recharge levels are usually low relative to the winter. These seasonal fluctuations in the shaft water levels continue to produce redox conditions and episodic decay of sulphide minerals. In addition to these fluctuating water levels, direct seepage through the river bed can also occur. When Wheal Jane mine re-opened in 1971 the workings of the 1930's were extended under the river to connect with the workings of Mount Wellington (Figure 1.7) This process entailed connection with the more older shallow workings, which were partially collapsed and during periods of high recharge it is considered that this has a direct effect on groundwater quality as the water in the shafts rises to connect with the water table; i.e., the base of the river bed.

Although the Wheal Jane tin mine has been declared abandoned it can be reopened and worked at any time in the future. Furthermore, metal processing continues at Wheal Jane Mill and each day water from this processing plant is discharged into the tailings lagoon. This water is, however, largely free of metals and the density of the water is less than that from the mine shafts. The effect of this is considered to be beneficial by enhancing metal settlement in the lagoon (Cambridge, pers.comm., 1995). This daily discharge is, however, causing the lagoon to fill prematurely and it will not reach it's projected life of 15 years but may fill earlier than predicted. How quickly this occurs is entirely dependant upon the supply of ore from the recently closed South Crofty tin mine (March 1998). The future of this mine is not yet settled and may be back in production in the very near future or the site developed for some other purpose.

1.5.3 Summary

Anthropogenicaly generated heavy metal contamination has been effectively polluting many south west rivers for several centuries so there is a considerable legacy from the past in addition to the most recent discharge from Wheal Jane. The old mines and associated spoil heaps affecting the Carnon catchment in particular (Figure 1.12) still remain potential sources of contamination. With the inactivity of South Crofty tin mine (tempory) metal mining has ceased in South West England, but the old abandoned workings continue to affect local rivers and groundwater.

Figure 1.12: View of derelict land and spoil heaps at Mt. Wellington Mine.

The extent of contamination depends on the original size of the operation and the length of time since they were last worked. The order of the size of operation and period of non working is Avon<Erme<Fowey<Carnon Valley. With time, worked faces will have leached away sufficiently to achieve chemical equilibrium.

Other sources of contamination are sewage and industrial effluents. Both have increased substantially this century with the growth in human population (Culver and Buzas, 1995) and both affect all the sample locations monitored here.

However, it was not possible within this research project to study these problems further.

1.6 Field descriptions

1.6.1 Generalities

Although the control (baseline) estuaries have been affected by metalliferous mining, this activity ceased in the last or early part of this century. Adjustment to heavy metal pollution has taken place as all three estuaries are classified as RE1 by the Environment Agency (Freshwater division), although they do not routinely carry out water analysis for concentrations of heavy metals. In addition, the Avon and Erme were control estuaries in the heavy metal pollution studies carried out by Bryan and Langston (1992). In the same study, metal concentration analysis of sediments from the Fowey Estuary are shown to be one order of magnitude lower than for Restronguet Creek (Bryan and Langston, 1992).

Restronguet Creek as its name implies, is a creek and not an estuary. However, although it does not have a direct opening to the sea, it does open out into Carrick Roads which is a wide marine inlet. Therefore, Restronguet Creek partially fits the definition of an estuary as being a partially enclosed body of water with a river input and an opening to the sea (Barnes, 1974). Restronguet Creek is tidally influenced but the tidal energy and range is marginally less great relative to the other estuaries Erme, Fowey, Avon and Carrick Roads which are macrotidal rias (Davidson *et al.*, 1991; Reid *et al.*, 1993). The sampling locations have two low and two high tides daily, with one spring and one neap tide each lunar month.

The control baseline estuaries run approximately either NNE-SSW (Avon and Erme) or near N-S (Fowey) but Restronguet Creek lies approximately NW-SE. The estuaries all drain into the Western Approaches of the English Channel.

With the exception of Fowey, silting of the estuaries has continued unchecked and sample station water depths are shallow. This is a particular problem with respect to Restronguet Creek which has been allowed to increase in sediment accumulation for approximately 100 years. Whitely (1881) found that the rate of accumulation was 6 - 10m at Devoran in the early - mid 19th century (approximately 30cm every five years) when mining activity was still extensive and that schooner navigation had been greatly reduced. This has resulted in the section of freshwater channel at the head of the Creek becomming deeply incised into the sediment column, forming steep mud banks on either side. In more recent times this extraordinary accumulation has partly been added to, via. the tailings lagoon, by material discharged from the mill at the modern Wheal Jane tin mine which remains in operation (although the tempory closure of South Croft tin mine has meant a decrease in the amount of ore supplied to the mill). The water depths at the sample stations in the upper reaches of Restronguet Creek, the Erme and Avon are <1.0m, increasing approximately to 2.0m at the lower stations (at high tide). The Fowey Estuary differs in that the lower port area is dredged daily to maintain sufficient depth for ship navigation serving the china clay port at Fowey (dredging began in 1906 and has only ceased temporally between 1939 and 1945). The water depth in the upper reaches is 1.2m and at Golant (old quay) the depth increases to 2.9m. Sediment is allowed to accumulate away from the main channel on the east side (e.g., at Mixtow Pill).

***i*) Restronguet Creek**

Restronguet Creek is tidal to Devoran road bridge (Figure 1.3) with a freshwater range of flow rates for the Carnon of 0.58 - 1.3$m^3 s^{-1}$. The River Kennell rate is gentler and the range of flow recorded at Ponsanooth is 0.06 - 0.26$m^3 s^{-1}$

(Hydrographic Office, Environment Agency). The present convergence of these two rivers has been caused to occur lower down than was the case in the 16th century (B. Simpson, pers. comm., 1993).

Figure 1.13: North-west view of the spit of land between the rivers Kennall and Carnon.

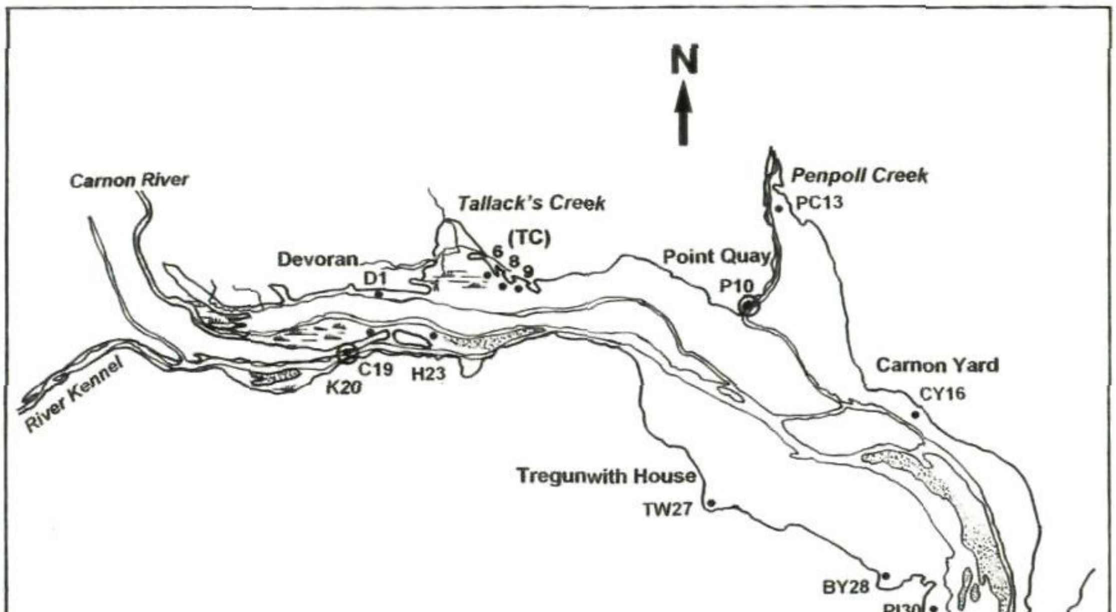


Figure 1.14: Map of the sample stations in Restronguet Creek.

The Creek has been extensively influenced by man, with the channel undergoing re-orientation a number of times (Simpson, 1991). The spit of land between the Kennell and Carnon rivers (Figures 1.13 and 1.14) was originally engineered to delay the convergence of the two rivers. The material used to build this barrier is slag waste derived from the old mines and smelters in the Creek (Section 1.5.1,*i*).

The mud flats bordering the Carnon River side of the spit now provide a suitable habitat for halophytic plants which occur in distinct zones. Prior to the discharge these plants were abundant and did not begin to reappear until summer 1993. Generally, however, the areas of saltmarsh are small (Figure 1.14). The more elevated better drained areas (above mean high tide, MHT) are colonised by *Armeria maritima* (thrift), but the areas which remain permanently moist are colonised by *Salicornia europea* which is a salt tolerant, pioneering species whose roots are at shallow depths, thus avoiding the sulphur rich deeper sediments. During periods of extensive drying, desiccation cracks appear in the mud and it is along these cracks that the *Salicornia europea* grows, above station C19. This phenomenon was common during the early stages of sampling but is less so now and may reflect a coarsening of the sediment which previously was too cohesive to allow the rhizomes to penetrate to the surface, unaided. Discrete areas at Devoran are colonised by *S. europea* and in the tidal mudflats of what remains of the original Narabo channel behind the quay at Devoran. Devoran forms the largest residential area adjacent to Restronguet Creek, but the industrial influence here is now negligible.

Tallack's Creek, is colonised by fuccoid algae and *S. europea*. This is an industrial archaeological site (Section 1.5.1, *i*) with some rock waste from the old mine streaming works submerged beneath the mud. Point Quay and Penpoll

Creek are predominately tidal mudflats with a small tributary stream entering the Creek from Penpoll. Moored boats are a permament feature at the head of Penpoll Creek. At Carnon Yard the old disused boat yard has recently been acquired by a new owner and has been extensively extended as a boat store and repair shop, but does not affect sample station CY16. This area constitutes the only major commercial influence in Restronguet Creek. The rocky foreshore leading down to station CY16 is colonised by *Fucus vesiculosus* and seasonally by *Enteromopha compressa*. The smaller boat yard (station BY28) on the south side of the Creek is mostly for storage. Along the shoreline at stations BY28 and TW27 the tidal mudflats are colonised by fucoid algae.

Sample station PI30 was free of algae cover for the first three years of sampling, but since the drought of summer 1995, *E. compressa* has regularly colonised this area of mudflat. Station CY16 is similarly affected. The south side of the Creek is mostly tree lined with little housing, while the north side is bordered by numerous residential buildings. Both sides of the Creek are dominated by arable and stock farming activities.

ii) Erme Estuary

The Erme sample area is relatively unspoilt and sparsely populated (Stubbles, 1995). The catchment area is 43.5 km^2 and the river channel is relatively straight and broad and has an average flow of 1.624 m^3s^{-1}. It is tidal for 6.3 km. Holbeton is the nearest village. Few boats are moored in this estuary because of the shallow draught.

The highest sample station (F1) is in the main channel and contains little substrate. At Holbeton Point (Figure 1.15) there are three sample stations (HP2, HP3 and HP4) close to the river channel.

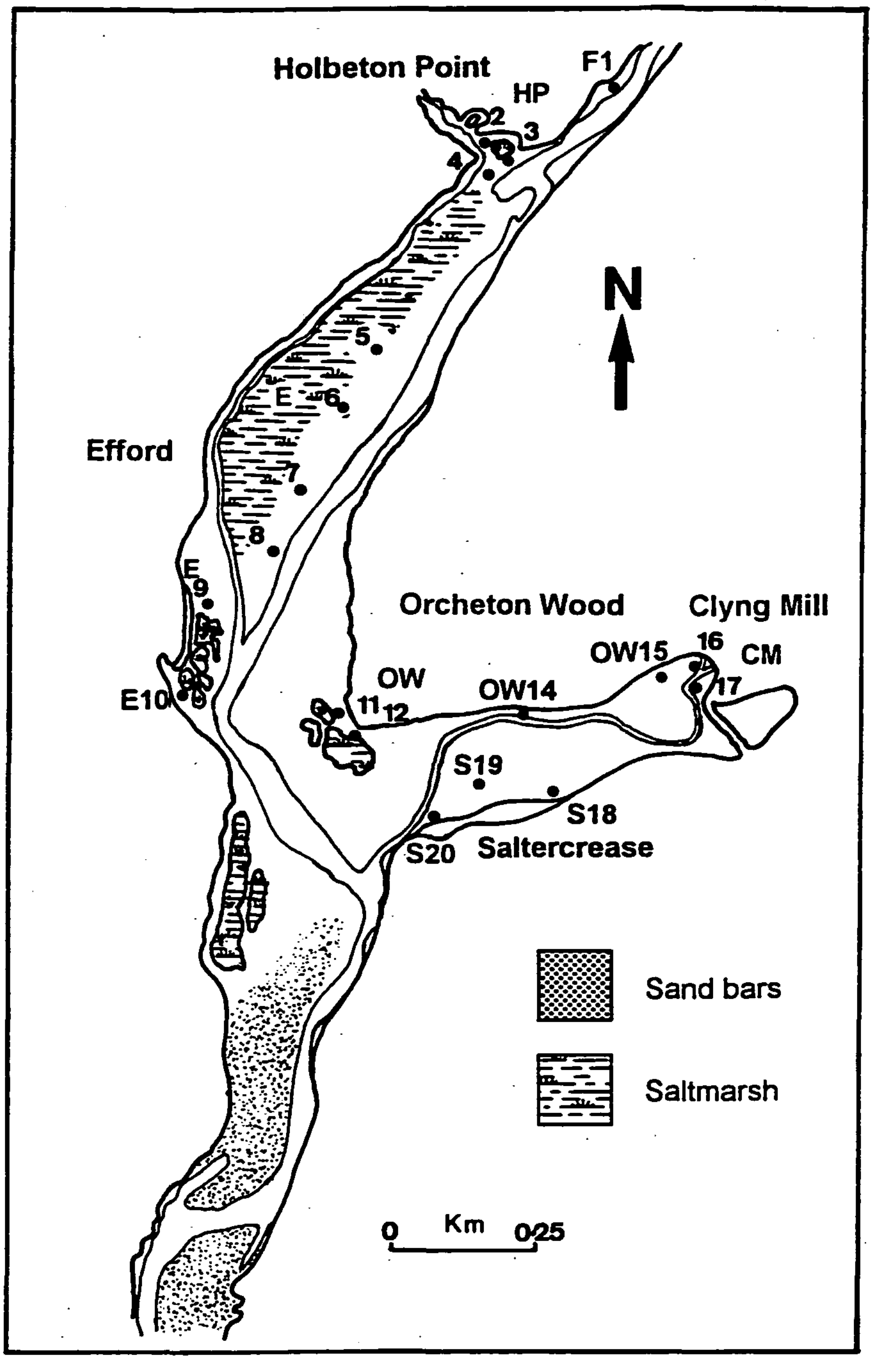


Figure 1.15: Map of the Erme Estuary sample stations.

At Holbeton Point there are discrete areas of saltmarsh hummock with a variety of saltmarsh flora including *Phragmites australis* and *Oenanthe cyocata* which colonise the area furthest from the channel and sample stations. The saltmarsh hummocks are colonised by *Halimione portulecoides*, *Puccinella maritima*, *Juncus gerardii*, *Filipendula ulmaria* and *Aster tripolium*. Station HP4 is one metre away from an outfall releasing treated sewage coming from the treatment works at Holbeton via. an open stream.

Stations E5, E6, E7, E8, E9 and E10 are situated in a small area of saltmarsh of raised hummocks. The saltmarsh is colonised by *Beta vulgaris martima*, *Juncus gerardii*, *Spartina townsendii*, *Elymus pychnocephalus*, *Glaux maritima*, *Phragmites*, *Armeria maritima* and *Carex extensa*.

Figure 1.16: View of Orcheton Wood from Efford saltmarsh on the Erme Estuary.

Across the river, stations OW11 and OW12 (Figures 1.15 and 1.16) are in a similar saltmarsh setting and have identical flora to stations E5-10. The other sample stations, OW14, OW15, CM16, CM17, S18, S19 and S20 lie within a small creek, Clyng Mill, which is predominantly tidal mudflat. The north shore of this creek has a rocky foreshore with some fucoid algae. At the head of the creek there is a small stream, running through disused trout ponds. Sample station S18 is reached via. a grass area colonised by *Halimione portulecoides*, *Puccinella maritima*, *Juncus gerardii*, *Filipendula ulmaria* and *Aster tripoium*. Station S20 is the lowest sample site and it is noticeable that the sediment is coarser below here with abundant shell debris.

***iii*) Fowey**

St Winnow is the upper most sampling point of the Fowey Estuary (Figures 1.17 and 1.18). The range of flow rates for the Fowey river are 3.3 - 4.1$m^3 s^{-1}$. Daily dredging occurs in the area between Fowey and Bodennick. The estuary is dominated by tidal mudflats colonised in discrete areas by fucoid algae. Areas of saltmarsh are absent in the sample area. The eastern shore is tree lined but the western shore is mostly clear in order to accommodate the mineral railway that is used to transport china clay to the port at Fowey (Figure 1.19). Both sides of the upper and mid-estuary are dominated by arable and stock farming with isolated hamlets.

At St Winnow (stations StW1 and 2; Figure 1.17) there is a small boat repair yard and over-wintering boat storage. The sample stations at the head of Lerryn Creek, LPO3 and RC4 are in a sparsly built-up residential area. At Cliff House (CH 5 and 6) there are only a few houses. A small hamlet surrounds the bridge area at Middle Penpoll (sample station PM7) and has a consent to discharge station. The two mudflat sampling stations at Mixtow Pill are immediately opposite the china clay port (Figure 1.19) and may be affected by china clay spillage. A pontoon has been constructed to accommodate the numerous leisure and small commercial boats moored at the Pill. Sample station PPH11 at the head of Pont Pill is a conservation area owned by the National Trust and has limited vehicular access.

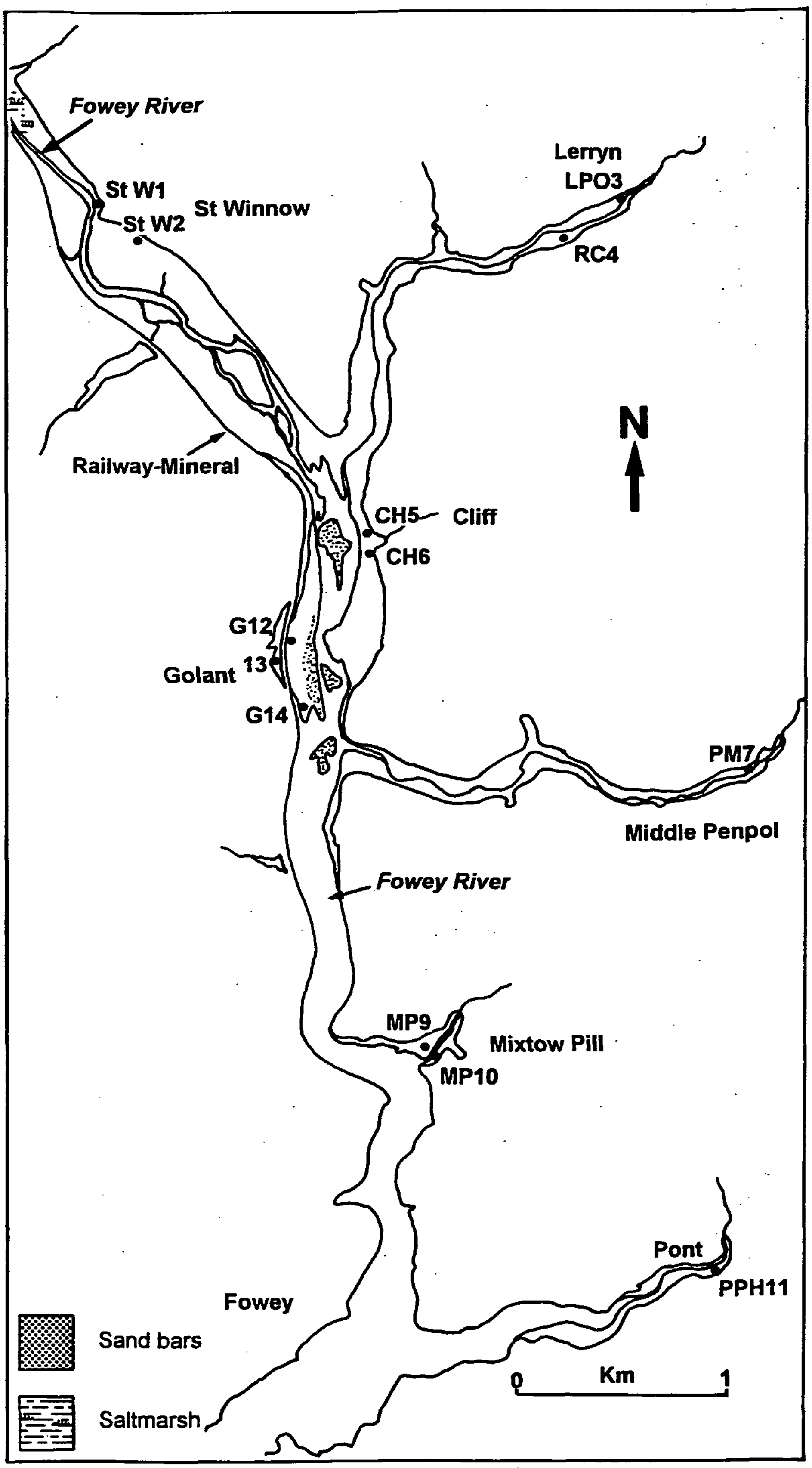


Figure 1.17: Map of the Fowey Estuary sample stations.

Figure 1.18: View of the mineral railway from St Winnow on the Fowey Estuary.

Figure 1.19: View of the china clay port from Mixtow Pill on the Fowey Estuary.

The only stations accessible on the west side are those at Golant. Sample stations G12 and G14 are in the main channel and below station G14 the substrate changes from medium to coarse beach sand. Sample station G13 is within the basin occupied by small fishing craft. Golant is densely inhabited and there are numerous residential houses and boat repair shops.

iv) Avon Estuary

The upper part of the Avon Estuary lies in an agricultural area with a small village, Aveton Gifford (Figure 1.20). However, at the mouth of the estuary, there are the popular recreational areas of Bigbury-on-Sea and Bantham. The estuary bends to an S shape near to the mouth and is generally less straight relative to the Erme and Fowey. The Avon is tidal for 7 km to Aveton Gifford Bridge and above this, the average channel flow recorded at Loddiswell is 3.122 m^3s^{-1}. The Avon has captured some of the freshwater flow originally draining into Kingsbridge Estuary. The catchment area is 102.3 km^2.

The upper estuary comprises a mixture of mudflat and areas of saltmarsh. Sample stations A1, A2, A5 and A9 are in tidal mudflats, adjacent to the river channel. The banks at sample stations A1 and A9 are colonised by *Halimione portulecoides*, *Puccinella maritima* and *Spartina townsendii* (the vegetated mound close to A9 is used each year by nesting swans). Stations A3 and A4 are in a small creek with saltmarsh hummocks which are colonised by *Beta vulgaris martina*, *Halimione portulecoides, Juncus gerardii*, *Spartina townsendii*, *Elymus pychnocephalus*, *Glaux maritima*, *Phragmites*, *Armeria maritima* and *Carex extensa*. Sample stations A6 and A7 are within the saltmarsh bordering the main channel and station A8 (Figure 1.20) is in a sediment bank separating a small bifurcation from the main channel. During the summer this mound is covered with

Entermorpha compressa and the substrate is less muddy compared to the upper estuary stations.

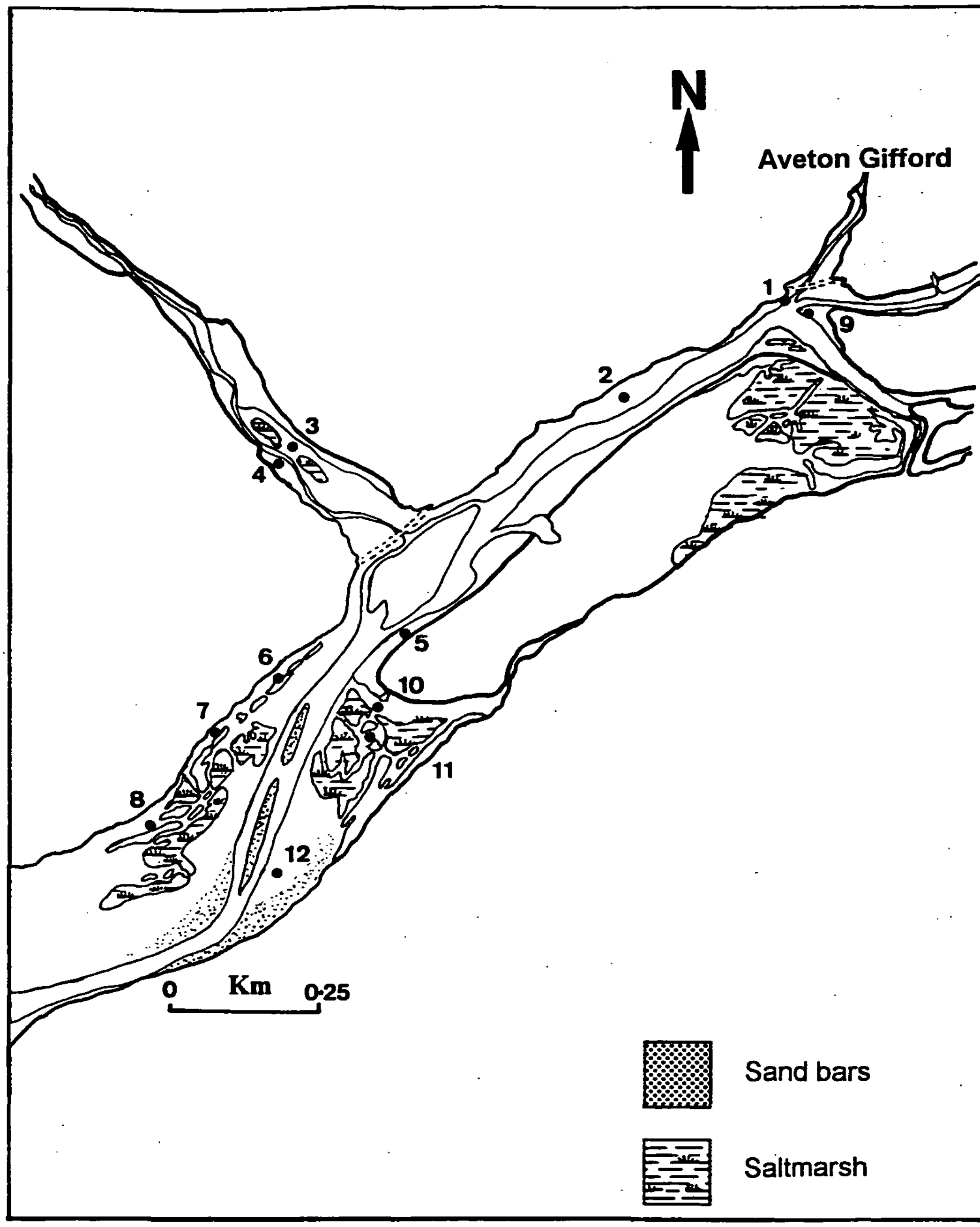


Figure 1.20: Map of the Avon Estuary sample stations. All stations are prefixed with the letter A. The full estuary is shown by Figure 1.11.

Sample station A10 is at the upper end of the saltmarsh on the east side and close to a storm drain. Sample station A11 lies within the saltmarsh which is colonised by the same species as are present on the west side. At sample station

A12 the substrate becomes distinctly coarser compared to the other sample stations and has abundant shell debris and is covered in the summer by *Entermorpha compressa*.

Figure 1.21: South-west view of the Avon Estuary.

Chapter Two

Methods and Materials

2.1 Field techniques

2.1.1 Abiotic variables

At the high tide preceding or following the low water sampling, salinity, temperature and pH were recorded using the following equipment: Atago refractometer (salinity); Digi-thermo meter (temperature); pH meter calibrated with buffer solutions of pH 4.0 and 6.0, in addition short range litmus papers were used to broadly check instrument accuracy.

Pore water was not obtained at every sampling attempt and the extractions did not always supply reliable salinity and pH data despite various methods being used. Of the methods used, drained or squeezed water from sediment samples taken for geochemical analysis (top few millimetres) was found to be the most successful but may have included residual tidal water. However, on particularly dry days, when evaporation was high, no water samples were collected by any of the methods used.

2.1.2 Sediment collection for foraminiferal analysis

For foraminiferal standing crop analysis, a sediment sample of known area (78.5cm^2) was removed using a plastic ring, 10cm in diameter. The definition of standing crop (Murray, 1991) used here is the number of stained foraminifera from an identical area of surface sediment removed at any one time. This enables comparison between samples in space and time. The ring was inserted into the sediment to a depth of 1cm and a flat sheet of plastic was slid beneath to lift the ring and sample away from the sediment surface. All the sample was removed to plastic jars and preserved in buffered foramalin, diluted to 10%. All equipment and footwear were washed free of mud at the site sampled to prevent cross contamination. With respect to Restronguet Creek replicate samples were taken during the initial two years of sampling.

On separate occasions, fresh sediment was taken from Restronguet Creek and temporarily stored in clean plastic jars not previously cleaned with detergent or acid washed. The jars were stored in a cool box containing ice blocks and were returned to the laboratory immediately. No more than 13 sites were sampled at any one time.

2.1.3 Sediment collection for geochemical analysis

For the geochemical and sedimentological analysis, sediment was removed from the surface to a depth of 0.5cm (oxidised layer only) and transferred to paper craft bags. As soon as possible they were oven dried at 60°C.

2.1.4 Short cores

Reconnaissance cores were taken at selected sites, using the Russian Peat Borer to a depth of 0.5m wherever possible. It was not always possible to get the borer down to the 0.5m level because of the shallow height of the bedrock. Cores were taken at stations TC6, TC9, TW27 (Restronguet Creek), E6 and E8 (Erme) and near StW1 (Fowey). A core was not taken from the Avon Estuary because of time constraints. Immediately after removal the cores were cut into 1cm thick slices and removed to glass vials (2cm diameter) containing buffered formalin and marked with the station number and depth. The thin layer of sediment adhering to the borer was left behind, thus reducing cross-contamination between levels. Core retrieval was very good and only the very top 0.5cm slice of each core from Restronguet Creek was lost. The Russian Peat Borer was used only for reconnaissance as there is potential for cross contamination (J. West, pers. comm., 1993). Longer cores were not taken as the results from the short cores indicated that extensive dissolution of calcareous taxa had taken place in Restronguet Creek (Stubbles *et al.*, 1996b) and hence would not have given any insights into the impact from past mining activity using foraminiferal species distribution and test condition.

2.2. Laboratory techniques

2.2.1 Foraminiferal analysis

The surface and core mud samples were wet sieved on a wide and deep 63μm sieve to remove the fines. When the water ran clear each residue was transferred to a bowl containing rose Bengal (1 gram per litre) and stored for 45 minutes (Murray, 1973), after which it was thoroughly rinsed and returned to the bowl to oven dry overnight at 60°C. Each sample was then hand sieved using 1mm, 500μm, 250μm, 125μm and 63μm meshes. No stained foraminifera were observed below the 1cm core level, so the species present can be classified as shallow infaunal and show no variation in vertical distribution (Buzas *et al.*, 1993).

2.2.2 Calculation for standing crop

There exists a natural bias in the distribution of stained tests between fraction size categories and it has been found that a greater abundance of stained individuals exists in the $\geq$125μm fraction relative to the $\geq$250 and $\geq$63μm fractions. In order to gain a sufficient sample size from each of the low abundance fractions, thus enabling valid statistical interpretations, more material is required from the

$\geq$250µm fraction, for example, relative to the $\geq$125µm. This split fraction method used here is similar to that of Martin and Liddell (1989). It was also found that greater accuracy was gained by splitting sediment with a narrower grain size range.

Each fraction was weighed (as a double check on splitting efficiency), split into aliquots using a small, two compartment, hand splitter (home made). The number of aliquots picked depended on the density of stained individuals but the aim was to pick between 100-250 stained individuals from the total sample. The low density and barren samples were picked throughout and all the foraminifera were removed (live plus dead). The high density samples were split down the furthest (1/16th) but a tally count of the unpicked aliquots showed close similarity and hence precision between them. The foraminifera were mounted on to a gridded slide. The total number of stained individuals (standing crop) in the sample was estimated by the product of each fraction picked and the sum of the fractions.

The equation used for this calculation is:

$$\Sigma \left[X(F_N)_i,\ X(F_N)_i,\ X(F_N)_i, \ldots \right] = SC\ (78.5cm^2)$$

Where X is the split proportion, i is the ith fraction from which F_N stained foraminifera were picked.

The Wild M7 binocular microscope was used for the routine picking and for identification. Relative abundances of the live and dead of each indigenous and transported-in species was determined from the first 150 individuals (approximately) of each fraction from the sample (Murray, 1991). The core material was picked of all foraminifera at 5cm intervals. When an anomoly was detected the centimetre levels above and below were also picked as necessary to improve the resolution.

2.2.3 Scanning Electron Microscopy techniques

Individual foraminifera were mounted on 10mm aluminium stubs using conductive adhesive mounting discs. The mounted sample material was coated with 8nm (nano metres) of gold. They were examined using the Jeol 5200 SEM operating at 15Kv and with a working distance of 20mm.

2.2.4 Laser Ablation ICP- sample preparation

A proportion of the fresh sediment was placed in a beaker with rose Bengal solution (Stubbles and Chenery, in prep.). Following immersion for 15 minutes, the sediment was piped into 1.8ml cryo-tubes using a catering piping bag with a plain nozzle (0.25cm diameter). The filled cryo-tubes were fitted into veins and placed in a Dewer containing liquid nitrogen. Later the cryo-tubes were transferred to a freeze-dryer for approximately 24 hours.

The freeze-dried sediment from each sample station was picked of all stained foraminifera and the individuals were mounted on to a gridded slide but not gummed. Using a no. 0000 brush dampened either with water or calgon solution (3.3g Sodium Hexametaphosphate and 0.7g Sodium Carbonate per 1 litre deionised water and diluted to a concentration of 1 in 10) the specimens were cleaned of all adhering material. It was found that the calgon solution was a more effective cleaner and did not affect the laser ablation process (Stubbles and Chenery, in prep.).

The individual resin stubs were made as follows. Buehler metset mounting resin was mixed with the hardener (5 drops per 20mls) and poured into the moulds previously cleaned with acetone and containing an identification disc.

Gentle tapping removed any air bubbles and the stubs were left for a few days to harden. The stubs were then pushed out of the moulds and left to harden further. Finally, these 'blanks' were ground down to the desired depth and stored. For mounting the cleaned foraminifera, a skim coat of freshly made resin (made as above) was applied to each stub surface, to which the foraminifera were immediately mounted and left to harden (Stubbles and Chenery, in prep.).

2.2.5 Laser Ablation ICP analytical technique

This analysis was carried out at the British Geological Society (Nottingham) by Simon Chenery and assisted by the author. For the analysis a Spectron Nd:YAG ultraviolet (266mm) laser system connected to a high quality Leitz optical microscope was used. The beam was focused onto the last or penultimate chamber which contained the stained protoplasm. The laser-microscope system utilises a custom-designed laser ablation chamber, with an optical quartz window which is flushed by an argon carrier gas stream. The argon gas stream transferred the ablated material to an inductively coupled plasma mass spectrometer (ICP-MS) via a polythene tube that connects the ablation cell to the ICP torch, using a modified dual-flow sample introduction system as described by Chenery and Cook (1993). The elements were determined via a VG Plasmaquad 2 Plus ICP-MS which ionises the samples and uses a quadrupole mass spectrometer to scan or peak jump to ions which have a mass to charge ratio in the range of 6-250. The ablation runs were randomised and the stubs were periodically switched around in order to reduce the effects of systematic error. In conjunction with the line diagrams of the stubs a written record of each analysis (laser ablation) was kept and was later used to match results with the amount of material ablated.

Data analysis was carried out using a Dell 486MX computer through dedicated ICP-MS software. This corrected the raw intensity data to isotopic abundance and instrument sensitivity for isotopes of different mass. These data were imported into an Excel spreadsheet and the relative concentrations were corrected after subtraction of the blanks and changes in analytical run. Values which fell below reliable detection limits were marked. The values derived were then converted to absolute concentrations as described by Querol and Chenery (1995) and then expressed as a ratio to Ca and multiplied by 100. The final values are described as arbitrary units of concentration.

The amount of material ablated is directly proportional to elemental concentration. It is necessary, therefore, to measure the size of the crater and relate this to the data. It was found during laser ablation that some of the foraminiferal tests (in part or whole tests) did not survive the process intact, resulting in more material being ablated. In conjunction with a written record made during laser analysis, scanning electron image analysis was carried out to measure each crater and hence, exclude those results derived from crater diameters greater than c.40µm (Stubbles and Chenery, in prep.).

2.2.6 Sediment grain size analysis

The Malvern Mastersizer laser detector (Department of Geographical Sciences) was used to determine the sediment grain size distribution. Only one sample batch for each location was analysed as it had been determined earlier that little variation was shown between seasonal and annual samples. However, two samples from station H23 were analysed (1992 and 1993), because field observations had shown that there was a change in the sediment grain size. The analysis of each sample was carried out twice to give a full range of particle size distribution using the focal lengths 1000mm and 45mm. Before each analysis a background reading scan was carried out. Preliminary processing involved the gentle dissagregation of a small block of dried sediment to form smaller aggregates which were then added to the mixer unit containing water. The obscuration level was checked and if below 10% dispersion was added until this value was achieved. When the optimum obscuration level of 10-20% was reached, the sample was measured. Dispersion was repeated for some samples to a maximum of three dispersals. The final obscuration and residual value was noted. All samples had a residual value of <1.5 (ratio of the results and background levels). Obscuration is a measure of the amount of laser light passing through the mixture of water and sediment and is an indication of how well the material is dispersed prior to detection. The residual value is an indication of how much at variance the data are to the background readings. A computer calculated the results and produced a graph with percentage and cumulative values for each sample. Material below 0.1μm was not detected.

2.2.7 Sediment mineralogical analysis - thin section and binocular microscopy

The thin sections were made to a thickness of c.30μm using sediment from each location. Using a polarising binocular microscope the slides were analysed in plane and crossed polarised transmitted light. Using typical optical techniques the properties of each mineral was determined and a representative area was quantified to establish the percentage proportions of each mineral. For mineral identification, with respect to the thin sections, Gribble and Hall (1985) was refered to and for natural light analysis Gribble (1988) was used. For the minerals featured by the SEM images Scott *et al.* (1998) was used to identify the heavy minerals.

In addition, a representative sample from each fraction from each sediment sample was analysed under a low power binocular microscope (Wild M7). The relative percentage proportions were estimated.

2.2.8 Sediment geochemical analysis

This work was carried out by technical and research staff in the Department of Environmental Sciences (University of Plymouth) following the method of Bryan and Langstone (pers. comm. W. Langston, 1996) which uses cold extractable 1M HCl. This method is not regarded as a determinant of "bioavailable" concentratiions but obtains data to give "extractable metal concentrations" (Luoma and Bryan, 1981; Bryan and Langston, 1992). The concentration of the acid was of sufficient strength (1M) to ensure extraction efficiency, overcoming the neutralising effects produced by the carbonate material stored in the sediments (Luoma and Bryan, 1981). The proportions of carbonate material increase down estuary (Chapter Four, Section 4.5.3) and may reduce extraction efficiency and hence, induce low metal concentrations.

Whole sediment from each sample plus duplicates and reference material were gently disaggregated prior to weighing and 0.5g of sediment (to 4 decimal places) was measured and to which 10mls of 1M HCl was added. The samples were shaken on a table for two hours and centrifuged for five minutes. The supernatant was decanted into volumetric flasks and made up to 50mls. Using flame (air-acetylene) AAS (atomic absorption spectroscopy) the solutions were analysed for Cu, Zn, As, Fe, Pb, Ni, Ca and Cd. For the analytes Sn, Al and Cr nitrous oxide-acetylene flame was used. For the determination of Fe, Ca and some Zn substantial dilutions had to be made. The analytes Cd and Cr were often below detection limits and marked as ND on the data spreadsheets.

The data obtained for the reference material indicated that elemental extraction was between 30 and 45% by this method (Appendix 1.1a). As there were only a few duplicate samples analysed reliable error data was not obtained. However, the difference between the duplicates and the sample was between 3% - 11% (Appendix 1.1a).

2.2.9 Determination of organic carbon and nitrogen

The ground sediment samples were pre-treated with concentrated HCl to remove the carbonate material. Each acidified sample was left to effervesce and dry out on a hot plate set at 50°C. When completely dry the sediment was re-ground and stored in sealed glass vials.

The carbon and nirtogen analysis was carried out at Plymouth Marine Laboratory with the guidance of Bob Head. Using a Cahn 25 dual nano-balance approximately 20mg of sediment was weighed into tin pressed capsules (5mm by 8mm), folded and crimped to seal in the sample. Each empty capsule had been weight normalised and zero-ed before use. The weights were recorded and entered into the computer program for analysis. In addition, 6 standards containing Acetanilide were prepared in the same way, with the weights varying from 0.1 to 1.0mg.

For analysis each sample was placed into the dispensing carousel and loaded onto the Carlo Erba NA 1500 Series 2 analyser which was pre-set at 1030°C. The method used follows that of Verado *et al.* (1990). Each sample takes approximately 2.5 minutes to analyse and compute the results which are expressed as percentages. All missing values were subsituted with the mean of the sample. The C/N ratio was calculated to determine available nutritional carbon which may be meaningful to the foraminifera and lower values (<25) indicate greater carbon decomposition (De Rijk, 1995).

2.2.10 Statistical analysis

The software packages Excel, SPSS (Statistical Package for Social Scientists) and the PRIMER programme of ordination by non-metric Multi Dimensional Scaling (MDS) were used to carry out various statistical analyses. The similarity files necessary to carry out MDS analysis were created using the PRIMER programme Bray-Curtis Similarity Cluster Analysis. Each MDS plot was arrived at through the enaction of a minimum of 10 random re-starts as recommended by the authors Clarke and Warwick (1994). The stress values featured on each MDS plot refer to the adequacy of each solution and in all cases the stress values are within a range (<0.1) specified by Clarke and Warwick (1994) as having "no prospect of misinterpretation". When variation between samples is low the MDS plots fail to show spatial relationships and tight sample clusters are formed.

Correlation coefficients have been applied as a primary indicator of association. Care has been taken to avoid induce correlations wherever possible when using closed data (i.e. ppm and percentages). Percentage proportions have been used only when compositional information was required (e.g., species and the proportion of deformed tests). For abundance information the raw data (e.g., standing crops) have been used. Correlation coefficient values $\geq$0.55 are accepted as significant (confidence limit - 95%). Higher values $\geq$0.7 are defined as strong (C.L. - 99%).

Chapter Three

Taxonomic Notes

3.1 Introduction

As this research is not taxonomic in nature but is an applied use of Recent benthic foraminifera, this chapter is not comprehensive. The chapter is divided into two sections, indigenous (living) and transported (dead) species because each group has been subjected to different statistical treatment. The indigenous species have to be fully validated due to their importance as *in situ* indicators and hence a full taxonomic treatment is given for each of the six species in Section 3.2, showing the original species name, the most recent reference to the name used (with the author/s and date), diagnosis, description, occurrence and, wherever necessary, remarks. For the transported-in species (Section 3.3) only the original, and most recent, reference are given together with a diagnosis. The same treatment is also applied to the classification of the testate amoebae as they are also introduced into the estuaries.

The classification follows that of Loeblich and Tappan (1964; 1988), Haynes (1973) and Murray (1971) with the addition of more recent references as shown in the text. The classification of the testate amoebae follows that of Loeblich and Tappan (1964) to genus and from Ogdon (1980) and Medioli and Scott, (1983) to species level. This is followed by Table 3.1 which shows the general distribution of these non-indigenous species (both the foraminifera and testate amoebae).

3.2 Indigenous foraminifera

Phylum **PROTOZOA** Goldfus, 1818

Subphylum **SARCODINA** Schmarda, 1871

Class **FORAMINIFERA** Lee, 1990

Subclass **GRANULORETICULOSIA** De Saedeleer, 1934

Order **FORAMINIFERIDA** Eichwald, 1830

Suborder **TEXTULARIINA** Delage & Hérouard, 1896

Family **RZEHAKINIDAE** Cushman, 1933

Genus ***MILIAMMINA*** Heron-Allen & Earland, 1930

Miliammina fusca (Brady)

Plate 1, Figures 1-5

Quinqueloculina fusca Brady, 1870: p.286, pl.11, fig. 2a-c. = *Miliammina fusca* (Brady), 1870; Bender, 1989a: p.296, pl.1, fig.6, pl.2, figs 1-7, pl.6, fig.3, 4,8, pl.13, fig.1, pl.16, fig.9.

Diagnosis: An elongate species of *Miliammina* with a terminal aperture containing a small tooth.

Description: Test free, agglutinated, elongate, slightly compressed and coiled in a quinqueloculine plan. The sutures are moderately depressed. The aperture is terminal with a small finely agglutinated tooth inside the outer lip.

Remarks: The contents of the test wall varies, the characteristics of the wall can be seen in Plate 1, Figs 4 and 5).

Occurrence: This species is absent in Restronguet Creek but commonly occurs in the upper estuarine/saltmarsh regions of the Fowey, Avon and Erme. In the upper saltmarsh/tidal flat areas of these locations, *M. fusca* is the dominant species and, occasionally, is the only stained species present.

Plate 1

Figure 1. *Miliammina fusca*, full view, Erme Estuary, station E5, winter 1993.

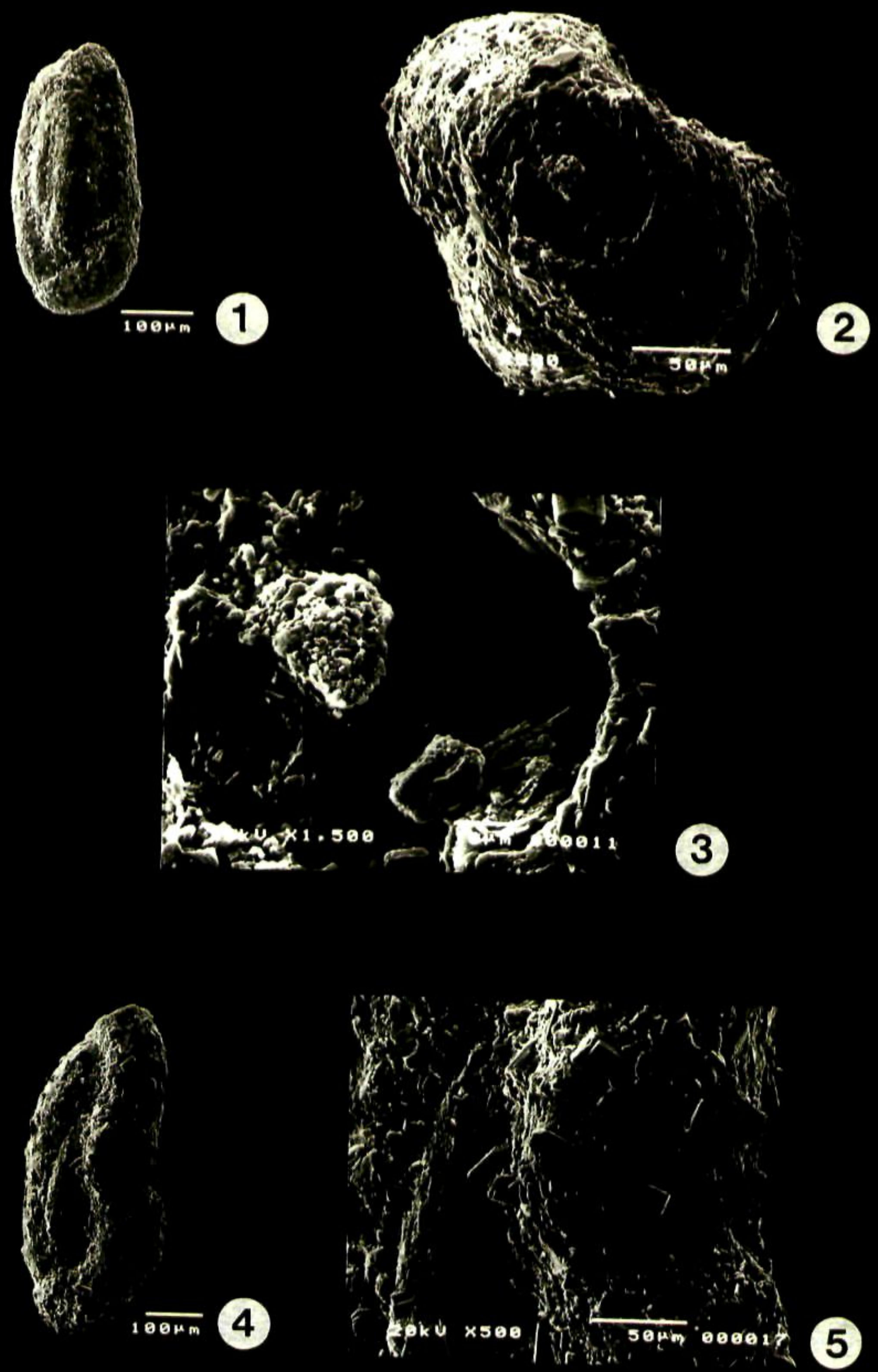
Figure 2. *Miliammina fusca*, aperture, Fowey Estuary, station StW2, spring 1994. The test wall is coarsely agglutinated but the small tooth is finely agglutinated.

Figure 3. Enlargement of apertural tooth in Figure 2.

Figure 4. *Miliammina fusca*, full view, Fowey Estuary, station StW2, spring 1994. Note the coarse agglutination, predominance of mineral grains and deformed test.

Figure 5. Enlargement of test wall in Figure 4.

Plate 1



Family **TROCHAMMINIDAE** Schwager, 1877

Subfamily **TROCHAMMININAE** Schwager, 1877

Genus ***JADAMMINA*** Bartenstein & Brand, 1938

Jadammina macrescens (Brady)

Plate 2, Figures 1-6

Trochammina inflata (Montagu) var. *macrescens* Brady, 1870: p.290, pl. 11, fig. 5a-c. = *Jadammina macrescens* (Brady) Brönnimann & Whittaker 1984, p. 305, figs 1-15.

Diagnosis: A subglobular species of *Jadammina* with numerous areal pore openings forming the aperture.

Description: Test free, low trochospiral, finely agglutinated and coiling sinistral about the proloculus (dorsal side) but involute on the umbilicus side (ventral). The aperture consists of one interio-marginal slit in a peripheral position with regard to the basal suture, with additional areal pore like openings.

Remarks: The test is composed of fine silt - sized grains, with an organic inner and outer organic lining (Bender, 1995). The multi-apertured openings (Plate 2, Figs 3-5) and the collapse of the test chambers on drying (Plate 2, Fig.6) are typical characteristics of this species. The multi-apertured openings distinguish this species from *J.balticammina* Brönnimann, Lutze and Whittaker, 1989.

Occurrence: *Jadammina macrescens* is present in low numbers in the Fowey, Avon and Erme mid - low estuarine mudflat areas, but is absent from Restronguet Creek.

Plate 2

Figure 1. *Jadammina macrescens*, spiral side, Avon Estuary, station A4, summer 1995. The chambers of this specimen have not collapsed (see Figure 6).

Figure 2. *Jadammina macrecsens*, umbilical side, Avon Estuary, station A4, summer 1995.

Figure 3. *Jadammina macrescens*, view of apertural face, Avon Estuary, station A3, autumn 1995. This view shows the multiple areal apertures common to this species.

Figure 4. Enlargement of apertural openings in Figure 3, showing less smooth and coarser agglutination around the areal apertures.

Figure 5. *Jadammina macrescens*, apertural face, Avon Estuary, station A3, autumn 1995. Shows coarse agglutination around the apertures.

Figure 6. *Jadammina macrescens*, station E6, Erme Estuary, summer 1991. Displaying collapsed chambers which are common to this species.

Plate 2

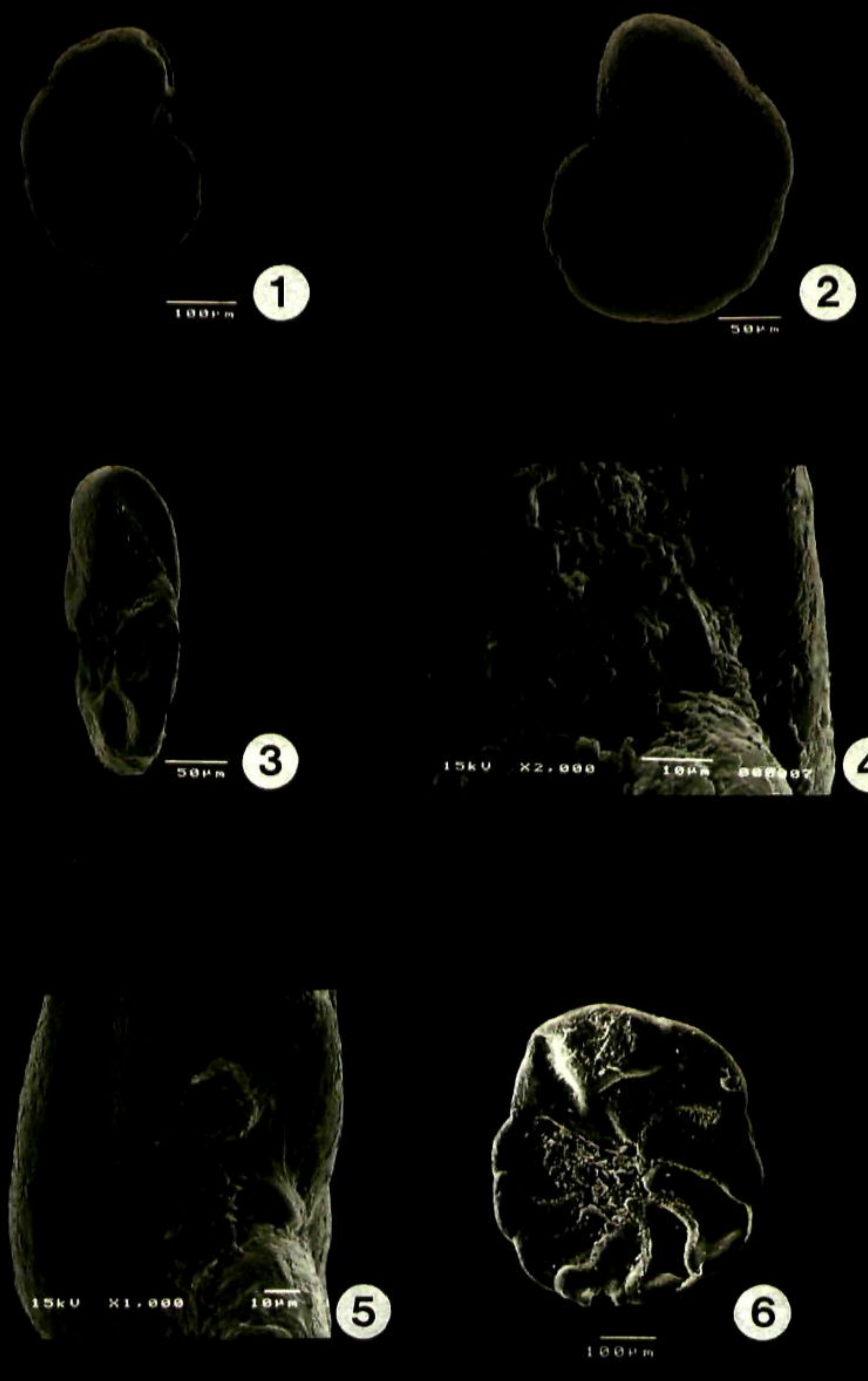

1
100µm
2
50µm
3
50µm
4
15kV X2,000 10µm
5
15kV X1,000 10µm
6
100µm

Plate 3

Figure 1. *Trochammina inflata*, spiral side, Avon Estuary, station A4, summer 1995.

Figure 2. *Trochammina inflata*, umbilical side, Avon Estuary, station A4, summer 1995. Showing the basal margin slit which forms the aperture.

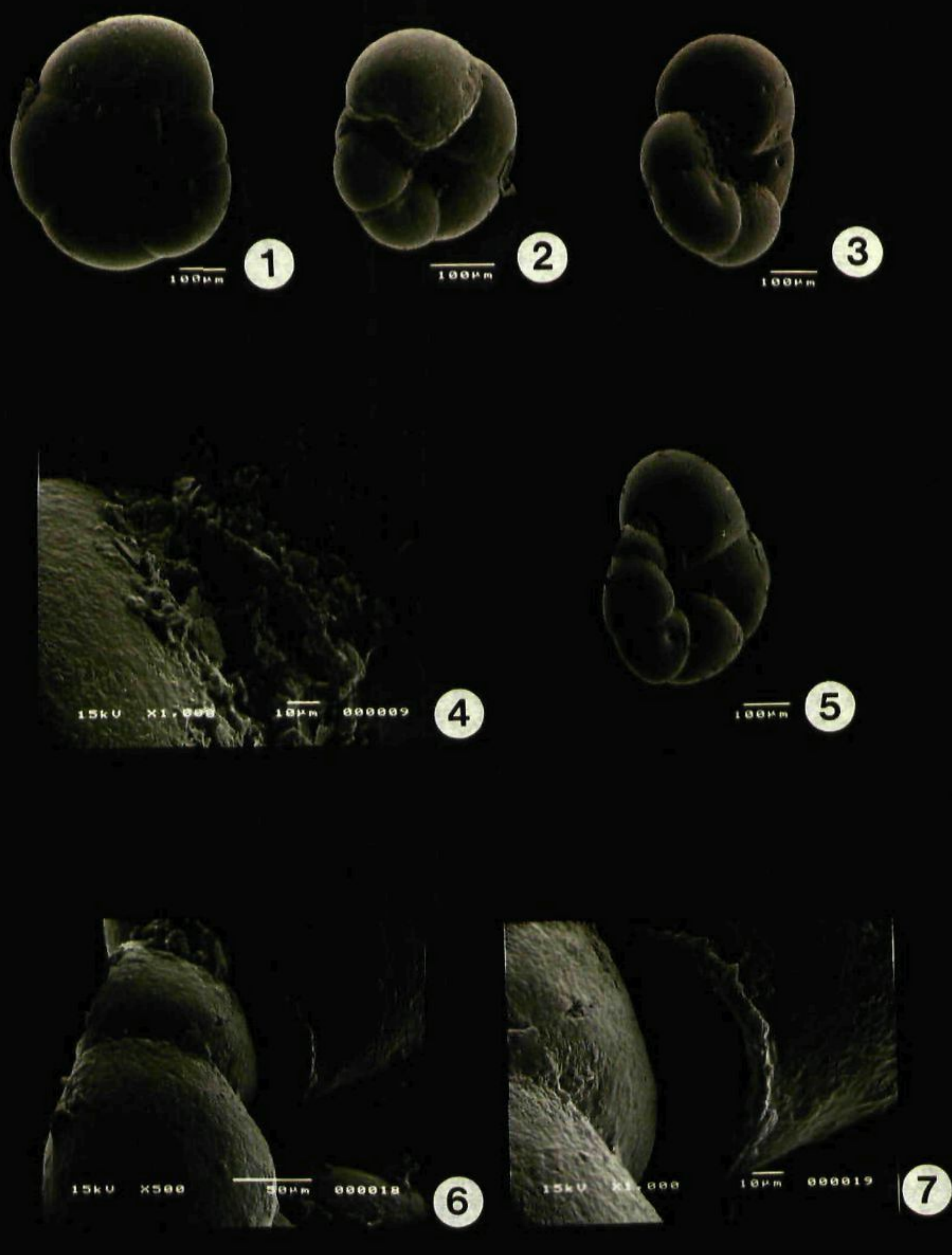
Figure 3. *Trochammina inflata*, oblique view of the apertural face, Avon Estuary, station A4, summer 1995. Displaying coarser agglutination within the area of the aperture relative to the remainder of the test.

Figure 4. Enlargement of aperture in Figure 3, showing an irregular slit partially sealed over by sedimentary grains.

Figure 5. *Trochammina inflata*, oblique view of the aperture, Fowey Estuary, station G12, summer 1994. Showing an arched basal margin slit (aperture).

Figures 6 and 7. Enlargement of aperture in Figure 5 showing the finely agglutinated lip.

Plate 3



1
100µm
2
100µm
3
100µm
4
15kV X1,000 10µm 000009
5
100µm
6
15kV X500 50µm 000018
7
15kV X1,000 10µm 000019

Genus ***TROCHAMMINA*** Parker & Jones, 1860

Trochammina inflata (Montagu)

Plate 3, Figures 1-7

Nautilus inflatus Montagu, 1808: p.81, pl.18, fig.3; Brown, 1844: pl.1, fig. 4.= *Trochammina inflata* (Montagu): Bronniman and Whitaker, 1984: p.312-313; de Rijk, 1995, p.35, pl.2, figs 1-3.

Diagnosis: A globose species of *Trochammina* with depressed sutures. Aperture is an interio-marginal slit.

Description: Test free, finely agglutinated and red-brown in colour. Low trochospiral with rounded periphery, deep, open umbilicus and coiled on the dorsal side but involute on the ventral side. Aperture is a slit bordered by a lip and is placed at the basal margin of the final chamber but is only visible on the ventral side.

Occurrence: The habitat of this species is in the mid - low marsh/tidal mudflat. It is present in the Fowey, Avon and Erme samples but is absent from Restronguet Creek.

Suborder **ROTALIINA** Délage & Hérouard, 1896

Family **ROTALIIDAE** Ehrenberg, 1839

Subfamily **ROTALIINAE** Ehrenberg, 1839

Genus ***AMMONIA*** Brunnich, 1772

Ammonia beccarii (Linné)

Plate 4, Figures 1-3

Nautilus beccarii Linné,1758: p.710. = *Ammonia beccarii* (Linné), Murray, 1971: p.151,pl.62,figs1-7

Diagnosis: A species of *Ammonia* with a rounded periphery and deep umbilicus.

Description: Test free, biconvex, subcircular in outline and calcareous hyaline. Test is dextral coiled on the dorsal side and involute on the ventral side with a depressed umbilicus containing pillars. Rounded periphery with flush sutures swept anti-clockwise on the dorsal side and depressed on the ventral side. Aperture visible on the ventral side; basal and umbilical internal foramen.

Remarks: This is a general description of *A.beccarii s.l.* and does not distinguish *A.beccarii* from *A.beccarii* f. *batavus* and *A.beccarii* f. *tepida*, the distribution of which are restricted to warmer and marine waters.

Occurrence: This species prefers the higher salinities and temperatures encountered towards the seaward end of estuaries and hence is found in larger numbers in the mid - low estuary areas of the Fowey, Avon and Erme Estuaries. Lower abundances are found in the upper creek areas of Restronguet Creek, but as with the other localites, it thrives in the more saline waters present in the lower Creek.

Genus ***ELPHIDIUM*** De Montfort, 1808

Elphidium williamsoni Haynes

Plate 4, Figures 4-6

Polystomella umbilicatula Williamsoni, 1858: p.42, pl.3, figs 81, 82. = *Elphidium williamsoni* Haynes n. sp., 1973: p.207, pl.24, fig.7, pl.25, figs 6,9, pl.27, figs 1-3.

Diagnosis: A rotund species of *Elphidium* with a rounded periphery and flat umbilicus.

Description: Test free, calcareous hyaline, rounded periphery. Numerous elongate retral processes overlap the sutures, the latter arching slightly in a clockwise direction (as seen from either side), depressed and straight. The umbilical boss is slightly proud on both sides, each side identical. The chambers are arranged into an involute planispiral form. Apertural face comprising an irregular array of pore openings along the basal suture of the last chamber.

Occurrence: This species colonises all areas of Restronguet Creek, but is restricted to the mid - low areas of the Avon and Erme Estuaries. In the Fowey Estuary *E. williamsoni* is present at all sample stations.

Genus **HAYNESINA**

Haynesina germanica (Ehrenberg)

Plate 4, Figure 7

Nonionina germanica Ehrenberg, 1840: p.23, pl.2, fig.1 a-g. = *Haynesina germanica* (Ehrenberg) Banner & Culver, 1978: p.184, fig.6; Loeblich and Tappan, 1988: p.616, pl.689, figs 1-4.

Diagnosis: An involute species of *Haynesina* with shallow depressed sutures containing numerous pores extending from the umbilicus and decreasing towards the periphery.

Description: Test free, calcareous, hyaline, planispiral and involute on both sides with a rounded periphery. Umbilicus slightly depressed with numerous pores extending from the umbilicus towards the periphery, becoming less in number, the pores form an arched depression, which constitute the sutures. Apertural face has a line of basal, interio-marginal pores slightly obscured by tubercules.

Occurrence: Commonly occurring throughout Restronguet Creek, the Fowey, Avon and Erme Estuaries.

Plate 4

Figure 1. *Ammonia beccarii*, spiral side, Restronguet Creek, station TW27, autumn 1996.

Figure 2. *Ammonia beccarii,* umbilical side, Restronguet Creek, station TW27, autumn 1996.

Figure 3. *Ammonia beccarii*, apertural view, Restronguet Creek, station TW27, autumn 1996. Showing the interiomarginal slit.

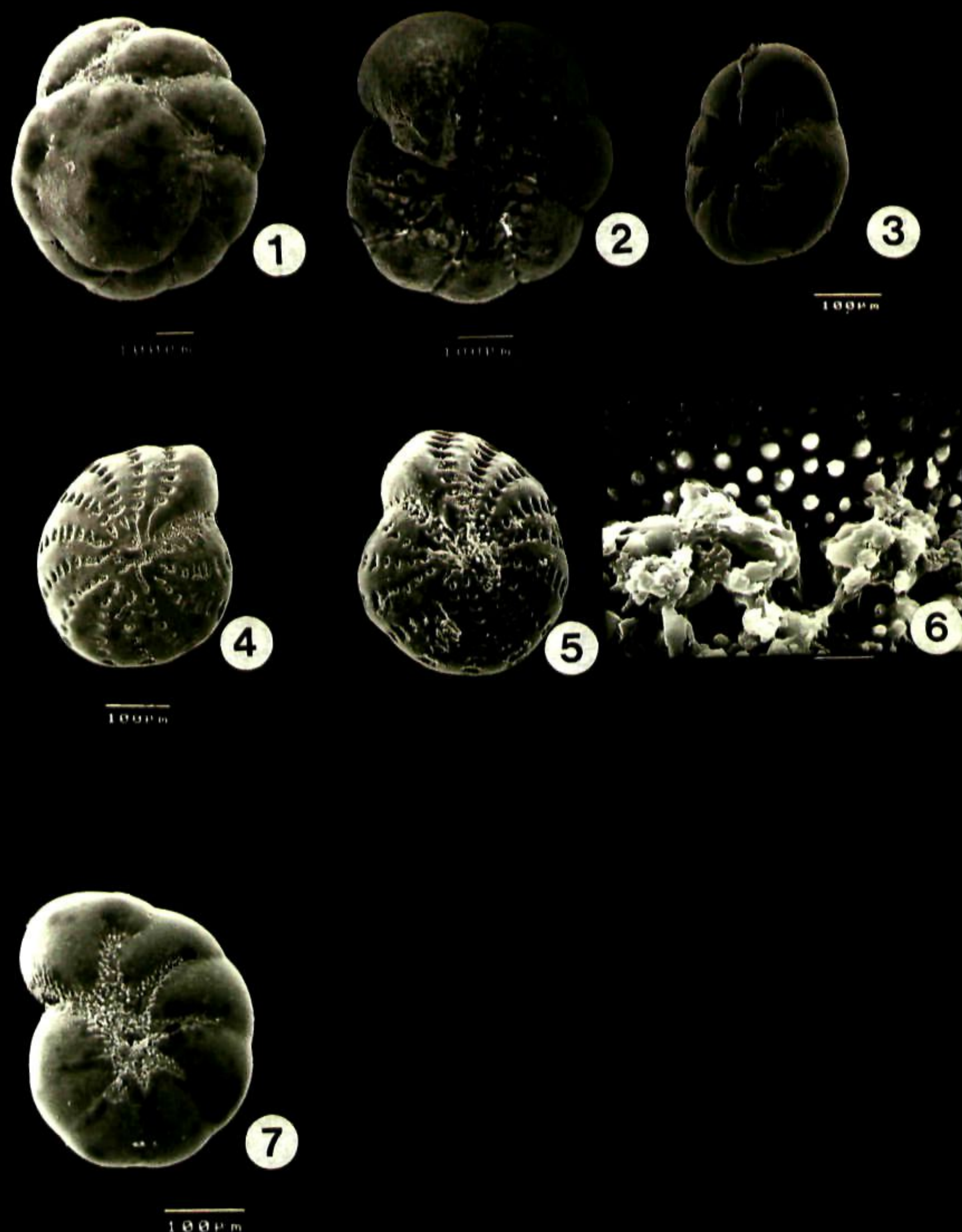
Figure 4. *Elphidium williamsoni*, Erme Estuary, station E8, autumn 1993. Showing the umbilical boss.

Figure 5. *Elphidium williamsoni*, reverse side, Erme Estuary, station E8, autumn 1993.

Figure 6. *Elphidium williamsoni*, apertural face, Erme Estuary, station E8, autumn 1993. Showing tubercles and the irregular openings just above the basal suture.

Figure 7. *Haynesina germanica*, general view, Erme Estuary, station E8, autumn 1993. Showing numerous tubercles which extend from the umbilicus out along the sutures.

Plate 4



3.3 Transported Taxa

Order **FORAMINIFERIDA** Eichwald, 1830

Family **HORMOSINIDAE** Haeckel, 1894

Genus ***Reophax*** De Montfort, 1808

Reophax moniliformis Siddell

Original reference: Siddall, 1886: p.54, pl.1, fig.2.
Recent reference: Murray, 1971: p.19, pl.2, figs 1-4.

Diagnosis: A cylindrical, tubular species of *Reophax* with 8-12 chambers which taper slightly towards the base. The aperture is terminal and round.

Remarks: Specimens stained with rose Bengal are only occasionally found and hence this species is not considered to be indigenous. The wall is coarsely agglutinated. Average length 1 mm.

Family **LITULOLIDAE** de Blainville, 1827

Haplophragmoides Cushman, 1910

Haplophragmoides wilberti Anderson

Original reference: Anderson, 1953: p.21, pl.4, fig. 7 a, b.
Recent reference: Todd and Lowe, 1961: p.19, pl.2, figs 1-4.

Diagnosis: A smooth, ovate, species of *Haplophragmoides*, with 8 chambers in the final whorl and a small umbilicus. The aperture is an interio-marginal slit.

Remarks: This species resembles *T.inflata* but has a flatter involute test and the colour is grey. The wall is finely agglutinated. Average diameter 1mm.

Family **TROCHAMMINIDAE** Schwager, 1877

Genus ***Trochammina*** Parker and Jones, 1859

Trochammina ochracea (Williamson)

Original reference: *Rotalina ochracea* Williamson, 1858: p.55, pl.4, fig.112, pl.5, fig.113.

Recent reference: Murray, 1971: p.37, pl.11, figs 1-5.

Diagnosis: A compressed species of *Trochammina*, concave on the umbilical side and with finely depressed sutures on the spiral side. Wide umbilicus and a slightly arched peripheral aperture.

Remarks: This species is found in the finer fractions and collected specimens rarely exceed 100µm.

Trochammina rotaliformis Heron-Allen and Earland

Original reference: ***Trochammina rotaliformis*** Heron-Allen and Earland, 1911: p.309.
Recent reference: Murray, 1971: p.39, pl.12, figs 1-5.

Diagnosis: An oval, depressed, species of *Trochammina* with a deep, narrow umbilicus and inter-umbilical aperture.

Remarks: This species has a deeper test relative to *T.ochracea* with a rounded periphery and with fine agglutination.

Family **ATAXOPHRAGMIIDAE** Schwager, 1877

Genus ***Eggerelloides*** Haynes, 1973

Eggerelloides scabrum (Williamson)

Original reference: *Bulimina scabra*, Williamson, 1858: p.65, pl.5, figs 136, 137.
Recent reference: Haynes, 1973: p.44, pl.2, figs 7, 8; figs 10, 11, text-fig.8 (1-4).

Diagnosis: A species of *Eggerelloides* which is trochospiral in initial stages but in adult stages of growth is triserial. Chambers increase in size with growth. The aperture is an interio-marginal slit.

Remarks: This species can show an irregular form with the last chambers disproportionately larger than the first formed. Finely agglutinated. Average length 0.8 - 1mm.

Family **CORNUSPIRIDAE** Schultze, 1854

Genus ***Cornuspira foliacea*** Cushman, 1928

Cornuspira foliacea (Philippi)

Original reference: *Orbis foliacea* Philippi, 1844: p.142, 147.
Recent reference: Loeblich and Tappan, 1964: C438.

Diagnosis: A species of *Cornuspira* with a depressed and evolute test. The last whorl opens out to form a large open aperture which is equal to half the overall diameter.

Family **MILIOLIDAE** Ehrenberg, 1839

Genus ***Spiroloculina*** d'Orbigny, 1826

Spiroloculina excavata d'Orbigny

Original reference: d'Orbigny, 1846: p.271, pl.16, figs 19-21.
Recent reference: Murray, 1971: p.55, pl.19, figs 1-3.

Diagnosis: A compressed elongate species of *Spiroloculina* with a terminal aperture containing a simple tooth. Test wall ornament comprises deep, smooth, longitudal grooving.

Genus ***Cyclogyra*** Wood, 1942

Cyclogyra involvens (Reuss)

Original reference: *Operculina involvens* Reuss, 1850: p.370, pl.46, fig. 20 a, b.
Recent reference: Murray, 1971: p.53, pl.18, figs 1-3.

Diagnosis: A compressed, planispiral and coiled species of *Cyclogyra* with a simple terminal aperture.

Genus ***Massilina*** Schlumberger, 1893

Massilina secans (d'Orbigny)

Original reference: *Quinqueloculina secans* d'Orbigny, 1826: ser.1, vol.7, p.303.
Recent reference: Loeblich and Tappan, 1988: p.335, pl.344, figs 1-7.

Diagnosis: A semi - round to elongate species of *Massilina* free of striations and an aperture containing a large bifid tooth.

Genus ***Pateoris*** Loeblich and Tappan, 1953

Pateoris hauerinoides (Rhumbler)

Original reference: *Quinqueloculina subrotunda* (Montagu) forma *hauerinoides* Rhumbler, 1936: pp.206, 217, 226, text-fig.167.
Recent reference: Loeblich and Tappan, 1988: 340, pl.350, figs 1-18.

Diagnosis: A species of *Pateoris* with an ovate to round compressed test with an arched aperture within the last chamber.

Genus ***Prygo*** Defrance, 1824

Prygo depressa (d'Orbigny)

Original reference: *Biloculina depressa* d'Orbigny, 1826: pl.8, fig.5.
Recent reference: Murray, 1971: p.71, pl.27, figs 1-4.

Diagnosis: A semi-rotund species of *Prygo* with an acute, irregular periphery. The aperture is a simple elongate slit.

Genus ***Quinqueloculina*** d'Orbigny, 1826

Quinqueloculina bicornis (Walker and Jacob) var. ***angulata*** (Williamson)

Original reference: *Serpula bicornis* Walker and Jacob, 1798: p.633, pl.14, fig.2.
Recent reference: Haynes, 1973: p.67, pl.7, fig.18, text-fig.16 (1-3).

Diagnosis: An ovate, globose species of *Quinqueloculina*, incised with longitudal grooves. The aperture is rectangular with a smooth tooth.

Quinqueloculina dimidiata Terquem

Original reference: Terquem, 1876: p.81, pl.40, fig.5 a-c.
Recent reference: Murray, 1971: p.61, pl.22, figs 5-8.

Diagnosis: A smooth species of *Quinqueloculina* with oblique sutures. The aperture is terminal and without a tooth.

Quinqueloculina lata Trequem

Original reference: Terquem, 1876: p.82, pl.11, fig.8 a-c.
Recent reference: Haynes, 1973: p.72, pl.7, figs 10-13.

Diagnosis: An oblong species of *Quinqueloculina* that is triangular in cross section. The sutures are slightly depressed. The aperture is terminal with a short, smooth tooth.

Quinqueloculina oblonga (Montagu)

Original reference: *Vermiculum oblongum* Montagu, 1803: p.522, pl.14, fig.9.
Recent reference: Murray, 1971: p.63, pl.23, figs 4-8.

Diagnosis: A rectangular species of *Quinqueloculina* oval in cross section. Terminal aperture containing a smooth tooth.

Quinqueloculina semimulum (Linné)

Original reference: *Serpula seminulum* Linné, 1758: p.786.
Recent reference: Haynes, 1973: p.74, pl.17, figs 14,19, pl.32, figs 1-3, text-fig.18 (1-4).

Diagnosis: An ovate species of *Quinqueloculina* with slightly compressed chambers. The terminal aperture has a simple tooth.

Family **NODOSARIIDAE** Ehrenberg, 1838

Genus ***Amphicoryna*** Schlumberger, 1881

Amphicoryna cf. A. scalaris (Batsch)

Original reference: *Nautilus (orthoceras) scalaris* Batsch, 1791: p.4, pl.2, fig.4 a,b.
Recent reference: Murray, 1971, p.77, pl.29, figs 1-4.

Diagnosis: A smoothed necked species of *Amphicoryna* with a terminal aperture enclosed with teeth.

Genus ***Astacolus*** De Montfort, 1808

Astacolus crepidulus (Fichtel and Moll)

Original reference: *Nautilus crepidula* Fichtel and Moll, 1798: p.107, pl.19, figs g-i.

Recent reference: Murray, 1971: p.77, pl.29, figs 5-6.

Diagnosis: A compressed species of *Astacolus* with oblique sutures and a terminal aperture surrounded by grooves.

Genus ***Lagena*** Walker and Jacob, 1798

Lagena clavata (d'Orbigny)

Original reference: *Oolina clavata* d'Orbigny, 1846: p.24, pl.1, figs 2,3.
Recent reference: Haynes, 1973: p.81, pl.32, fig.1, pl.13, fig.1.

Diagnosis: A smooth species of *Lagena*, clavate outline with smooth, moderately long neck and a short basal spine.

Lagena interrupta Williamson

Original reference: *Lagena striata* (Montagu) var. *interupta* Williamson, 1848: p.14, pl.1, fig.7.
Recent reference: Murray, 1971: p.83, pl.32, figs 1-5.

Diagnosis: A subglobose, ribbed species of *Lagena* with a long, hexagonal patterned, slender neck. The base is ornamented with small tubercles forming two concentric rings.

Lagena laevis (Montagu)

Original reference: *Vermiculum laeve* Montagu, 1803: p.524, pl.1, fig.9.
Recent reference: Haynes, 1973: p.84, pl.12, fig.2.

Diagnosis: A smooth, egg-shaped species of *Lagena* devoid of any ornamentation.

Lagena perclucida (Montagu)

Original reference: *Vermiculum perclucida* Montagu, 1803: p.525, pl.14, fig.3.
Recent reference: Haynes, 1973: p.86, pl.12, fig.5, pl.13, fig.5.

Diagnosis: A globular species of *Lagena* strongly ribbed at the base and with a long neck ornamented by widely spaced oblique ribs.

Lagena semistriata Williamson

Original reference: *Lagena striata* (Montagu) var. ß *semistriata* Williamson, 1848: p.14, pl.1, figs 9,10.

Recent reference: Haynes, 1973: p.87, pl.12, fig.6, pl.13, fig.4.

Diagnosis: An oval species of *Lagena* with numerous fine ribs at the base. The neck is ornamented with near straight, discontinuous ribs.

Lagena substriata Williamson

Original reference: Williamson, 1848: p.15, pl.2, fig.12.
Recent reference: Haynes, 1973: p.89, pl.12, fig.11, pl.13, figs 6, 11.

Diagnosis: An elongate species of *Lagena* with numerous fine ribs which extend up to the aperture from above the basal circlet of tubercles. The neck is short and contains fewer ribs.

Lagena sulcata (Walker and Jacob)

Original reference: *Serpula (Lagena) sulcata* Walker and Jacob, 1798: p.634, pl.14, fig.5.
Recent reference: Loeblich and Tappan, 1988: p.415, pl.455, figs 12, 13, 15-17.

Diagnosis: A globular species of *Lagena* ornamented with strong ribs and has a relatively short, smooth neck except for the presence of small tubercles.

Lagena tenuis (Bornemann)

Original reference: *Ovulina tenuis* Bornemann, 1855: p.317, pl.12, fig.3 a,b.
Recent reference: Murray, 1971: p.89, pl.35, figs 1-2.

Diagnosis: An oval species of *Lagena* with fine oblique ribs extending from the base of the neck to the aperture. The main body is smooth but the base is ornamented by short ribs.

Procerolagena gracilis (Williamson)

Original reference: *Lagena gracilis* Williamson, 1848: p.13.
Recent reference: Loeblich and Tappan, 1988: p.416, pl.455, fig.2.

Diagnosis: An elongate species of *Lagena* with dual, parallel margins tapering to an aplicate base. The test has faint to strong striae or costae.

Genus ***Lenticulina*** Lamarck, 1804

Lenticulina peregrina (Schwager)

Original reference: *Cristellaria peregrina* Schwager, 1866: p.245, pl.7, fig.89.
Recent reference: Murray, 1971: p.89, pl.35, figs 3-5.

Diagnosis: An oval species of *Lenticulina* with a terminal aperture containing short radiating slits.

Family **POLYMORPHINIDAE** d' Orbigny, 1839

Genus ***Globulina*** d' Orbigny, 1839

Globulina gibba d'Orbigny

Original reference: *Polymorphina* (*Globulina*) *gibba* d'Orbigny, 1826: p.266.
Recent reference: Loeblich and Tappan, 1988: p.419, pl.457, figs 6, 7.

Diagnosis: An oval species of *Globulina* with flush, oblique sutures and a terminal radiate aperture.

Globulina d'Orbigny var. ***myristiformis*** (Williamson)

Original reference: *Polymorphina myristiformis* Williamson, 1858: p.73-4, pl.16, figs 156, 157.
Recent reference: Murray, 1971: p.91, pl.36, figs 4-8.

Diagnosis: A globular species of *Globulina* with coarse ribs from the base to the aperture. The aperture is terminal containing circular openings.

Genus ***Guttulina*** d' Orbigny, 1839

Guttulina lactea (Walker and Jacob)

Original reference: *Serpula lactea* Walker and Jacob, 1798: p.634, pl.14, fig.4.
Recent reference: Boltovskoy, 1976: p.34, pl.17, figs 12-14.

Diagnosis: An ovate species of *Guttulina* with spirally arranged chambers in 5 planes. The sutures are distinct and slightly depressed.

Family **GLANDULINIDAE** Reuss, 1860

Genus ***Glandulina*** d' Orbigny, 1839

Glandulina ovula d'Orbigny

Original reference: d'Orbigny, 1846: p.30.
Recent reference: Jones, 1994: p.71, pl.61, fig.6.

Diagnosis: An elongate species of *Glandulina* tapered at each end and circular in cross section.

Genus ***Fissurina*** d' Orbigny, 1850

Fissurina lagenoides (Williamson)

Original reference: *Entosolenia marginata* var. *lagenoides* Williamson, 1848: p.11, pl.1. figs 25, 26.
Recent reference: Rouvillois, 1976: p.13, pl.2, figs 7, 8.

Diagnosis: An oval, compressed species of *Fissurina* with a parallel peripheral margin containing coarse, irregular ribs and terminating at the base a short neck.

Fissurina lucida (Williamson)

Original reference: *Entosolenia marginata* (Montagu) var. *lucida* Williamson, 1848: p.17, pl.2, fig.17.
Recent reference: Haynes, 1973: p.95, pl.14, figs1, 2, text-fig.20, (3, 4).

Diagnosis: A compressed oval species of *Fissurina*. The aperture is a terminal slit.

Fissurina marginata (Montagu)

Original reference: *Serpula* (*Lagena*) *marginata* Montagu, 1803: Walker and Boys, 1784: p.3, tab.1, fig.7.
Recent reference: Bornmalm, 1997: p.41, fig. 17 d-e.

Diagnosis: A semi-ovate species of *Fissurina* with a slightly compressed, smooth test with a narrow keel which bifurcates around the oval terminal aperture.

Fissurina orbignyana Seguenza

Original reference: Seguenza, 1862: p.66, pl.2, figs 19, 20.
Recent reference: Murray, 1971: p.99, pl.40, figs 1-5.

Diagnosis: An ovate species of *Fissurina* with a deep, three fold keel. The central keel bifurcates around the aperture.

Genus ***Oolina*** d'Orbigny, 1839

Oolina hexagona (Williamson)

Original reference: *Entosolenia squamosa* (Montagu) var. *hexagona* Williamson, 1858: p.13, pl.1, fig.32.
Recent reference: Haynes, 1973: p.107, pl.14, figs 12, 13, pl.15, figs 3, 6.

Diagnosis: A globular species of *Oolina* with a distinct hexagonal pattern of raised ribs ending at the base as a small boss.

Oolina lineata (Williamson)

Original reference: *Entosolenia lineata* Williamson, 1858: p.18, pl.2, fig.18.
Recent reference: Haynes, 1973: p.109, pl.14, figs 8-10.

Diagnosis: An ovate species of *Oolina* with fine longitudal striae and a blunt terminal aperture.

Oolina melo d'Orbigny

Original reference: d'Orbigny, 1839: p.20, pl.5, fig.9.
Recent reference: Murray, 1971: p.93, pl.37, figs 4-6.

Diagnosis: A globular species of *Oolina* with an irregular pattern of raised ribs.

Oolina squamosa (Montagu)

Original reference: *Vermiculum squamosum* Montagu, 1903: p.526, pl.14, fig.2.
Recent reference: Haynes, 1973: p.110, pl.14, fig.14, pl.15, figs 4, 5.

Diagnosis: A semi-globula species of *Oolina* with raised ribs producing a regular pattern.

Oolina williamsoni (Alcock)

Original reference: *Entosolenia williamsoni* Alcock, 1865: p.193.
Recent reference: Haynes, 1973: p.111, pl.14, figs 15-17; pl.15, figs 1,2,7.

Diagnosis: An ovate species of *Oolina* with longitudinal grooves separated by strong ribs which pass into a mesh pattern of ribs which terminate at the base of a short, smooth neck.

Family **BULIMINIDAE** Jones, 1875

Genus ***Buliminella*** Cushman, 1911

Buliminella elegantissima d'Orbigny

Original reference: d'Orbigny, 1839: p.51.
Recent reference: Loeblich and Tappan, 1988: p.522, pl.572, figs 7-11.

Diagnosis: A species of *Bulimina* with gently depressed, diagonal sutures. The aperture has a raised lip.

Genus ***Bulimina*** d'Orbigny 1826

Bulimina gibba Farnasini

Original reference: Famasini, 1902: p.378, pl.O, figs 32,34.
Recent reference: Haynes, 1973: p.121, pl.21, pl.10, fig.14, text-fig.24 (10-17).

Diagnosis: An inflated triserial species of *Bulimina* with chambers increasing in size with addition and occasionally with tubercles following the lower edges.

Bulimina marginata d'Orbigny

Original reference: d'Orbigny, 1826: 76.
Recent reference: Bommalm, 1997: p.9, fig.18L.

Diagnosis: An elongate-ovate, triserial species of *Bulimina*. The ends of the chambers extend outwards and the lower edge is bordered by small blunt tubercles.

Genus ***Stainforthia*** Hofker, 1956

Stainforthia fusiformis (Williamson)

Original Reference: Bulimina pupoides Williamson, 1858: p. 63, fig. 129, p. 130.
Recent reference: Haynes, 1973: 124, pl.5, figs 7, 8.

Diagnosis: An elongate, fusiform species of *Stainforthia*.

Family **BOLIVINITIDAE** Cushman, 1927

Genus ***Bolivina*** d'Orbigny, 1839

Bolivina pseudoplicata Heron-Allen and Earland

Original reference: Heron-Allen and Earland, 1930: p.81, pl.3, figs 36-40.
Recent reference: Haynes, 1973: p.132, text-fig.25 (20, 21), pl.10, fig.3, pl.11, fig.7.

Diagnosis: A compressed lanceolate species of *Bolivina* with an irregular pattern of raised processes.

Genus ***Brizalina*** Costa, 1856

Brizalina cf. B. pseudopunctata (Höglund)

Original reference: *Brizalina cf. B. pseudopunctata* (Höglund), 1947: p.273-4, pl.124, fig. 5 a,b, pl.32, figs 23, 24, text-figs 280,281, 287.
Recent reference: Murray, 1971: p.109, pl.44, figs 3-6.

Diagnosis: A lanceolate species of *Brizalina* with oblique depressed sutures ornamented by large pores.

Brizalina spathulata (Williamson)

Original reference: *Textularia variabilis* Williamson var. *spathulata* Williamson, 1858: p.76, pl.16, figs 164, 165.
Recent reference: Murray, 1971: p.111, pl.45, figs 1-4.

Diagnosis: A compressed species of *Brizalina* with an acute periphery and slightly depressed sutures, but without longitudinal costae.

Brizalina variabilis (Williamson)

Original reference: *Textularia variabilis* Williamson, 1858: p.76, pl.6, figs 162, 163.
Recent reference: Murray, 1971: p.113, pl.46, figs 1-3.

Diagnosis: A species of *Brizalina* with deep, oblique sutures and a coarse perforate wall of which each pore forms a deep cone.

Family **PLEUROSTOMELLIDAE** Reuss, 1860

Genus ***Parafissurina*** Silvestri, 1904

Parafissurina malcomsoni (Wright)

Original reference: *Lagena Laevigata* (Reuss) var. *malcolmsoni*, Wright, 1911: p.4, pl.11, figs 1, 2.
Recent reference: Murray, 1971: p.101, pl.41, figs 1-4.

Diagnosis: An elongate species of *Parafissurina* with a flared keel. The aperture comprises a slit.

Family **CASSIDULINIDAE** d'Orbigny, 1839

Genus ***Cassidulina*** d'Orbigny, 1826

Cassidulina obtusa Williamson

Original reference: Williamson, 1858: p.69, pl.6, figs 143-144.
Recent reference: Murray, 1971: p.189, pl.79, figs 1-6.

Diagnosis: A subglobular species of *Cassidulina* with depressed sutures. Aperture is a slit containing a lip on the lower edge.

Family **CERATOBULIMINIDAE** Cushman, 1927

Genus ***Lamarckina*** Berthelin, 1881

Lamarckina haliotidea (Heron-Allen and Earland)

Original reference: *Pulvinulina haliotidea* Heron-Allen and Earland, 1911: p.338, pl.11, figs 6-11.
Recent reference: Murray, 1971: p.205, pl.86, figs 1-6.

Diagnosis: A species of *Lamarckina* with chambers arranged into a convex spiral and an acute periphery.

Family **SPIRILLINIDAE** Reus, 1862

Genus ***Spirillina*** Ehrenberg, 1843

Spirillina vivipara Ehrenberg

Original reference: Ehrenberg, 1843: p.402.
Recent reference: Loeblich and Tappan, 1988: p.304, pl.318, figs 4-7.

Diagnosis: A compressed, coarsely perforate species of *Spirillina*.

Family **PATELLINIDAE** Rhumbler, 1906

Genus ***Patelina*** Williamson, 1858

Patellina corrugata Williamson

Original reference: Williamson, 1858: p.46, pl.3, figs 86-89.
Recent reference: Loeblich and Tappan, 1988: p.306, pl.320, figs 4-14.

Diagnosis: A plano - convex species of *Patelina* with a surface ornamented with pits and shallow ridges. The aperture has a flared flap.

Family **ASTERIGERINIDAE** d'Orbigny, 1839

Genus ***Asterigerinata*** Bermúdez, 1949

Asterigerinata mamilla (Williamson)

Original reference: *Rotalina mamilla* Williamson, 1858: p.54, pl.4, figs 109-111.
Recent reference: Haynes, 1973: p.164, pl.18, figs 1-4, pl.19, figs 7, 9; text-fig.32 (1-5).

Diagnosis: A high trochospiral, plano - convex species of *Asterigerinata* with a line of pores defining the coiling chambers on the dorsal side. The aperture is a narrow arch with a lip.

Family **CANCRISIDAE**

Genus ***Cancris*** De Montfort, 1808

Cancris auricula (Fichtel and Moll)

Original reference: *Nautilus auricula* Fichtel and Moll, 1798: p.108, pl.20, figs a-f.
Recent reference: Murray, 1971: p.137, pl.57, figs 1-7.

Diagnosis: An elongate, compressed species of *Cancris* with shallow sutures and a sharp periphery.

Family **CIBICIDIDAE** Cushman, 1927

Genus ***Cibicides*** De Montfort, 1808

Cibicides lobatulus (Walker and Jacob)

Original reference: Nautilus lobatulus Walker and Jacob, 1798: p.642, pl.14, fig.36.
Recent reference: Bommalm, 1997: p.76, fig.26 d-f.

Diagnosis: An irregular, biconvex species of *Cibicides* with lobed-shaped chambers.

Planorbulina mediterranensis d'Orbigny

Original reference: d'Orbigny, 1826: p.280, vol.7, pl.14, figs 4-6.
Recent reference: Murray, 1971: p.179, pl.75, figs 1-6.

Diagnosis: A species of *Planorbulina* with depressed sutures and cyclically arranged chambers.

Family **DISCORBIDAE** Ehrenberg, 1838

Genus ***Buccella*** Andersen, 1952

Buccella frigida (Cushman)

Original reference: *Pulvinulina frigida* Cushman, 1921: p.12.
Recent reference: Ishman and Foley, 1996: p.218, pl.2, fig.1.

Diagnosis: A biconvex species of *Buccella* with flush sutures and tubercular ornamentation on the umbilical side.

Genus ***Gavelinopsis*** Hofker, 1951

Gavelinopsis praegeri (Heron-Allen and Earland)

Original reference: *Discorbina praegeri* Heron-Allen and Earland, 1913: p.122.
Recent reference: Loeblich and Tappan, 1988: p.560, pl.608, figs 6-12.

Diagnosis: An evolute species of *Gavelinopsis* with flush sutures and carinate periphery. The aperture is a low interio-marginal-extraumbilical slit.

Genus ***Rosalina*** d'Orbigny, 1826

Rosalina anomala Terquem

Original reference: Terquem, 1875: p.438, pl.5, fig.1.
Recent reference: Haynes, 1973: p.150, pl.17, figs 1-3, pl.19, fig.2, pl.30, figs 1, 2; text-fig.28.

Diagnosis: A species of *Rosalina* with coarse pores on the spiral side but which are absent on the umbilical side.

Rosalina williamsoni (Chapman and Parr)

Original reference: *Rotalina nitida* Williamson, 1858: p.54, pl.4, figs 106-108.
Recent reference: Haynes, 1973: p.162, pl.17, figs 13-15; text-fig.31 (1-4).

Diagnosis: A keeled and finely perforate species of *Rosalina* with an umbilical boss.

Family **GLABRATELLIDAE** Loeblich and Tappan,

Genus ***Glabratella*** Dorren, 1948

Glabratella milletti (Wright)

Original reference: *Discorbina milletti* Wright, 1911: p.13, pl.2, figs 14-17.
Recent reference: Murray, 1971: p.139, pl.58, figs 1-4.

Diagnosis: A species of *Glabratella* with flush chambers and a carinate periphery.

Family **NONIONIDAE** Schultze, 1854

Genus ***Nonion*** De Montfort, 1808

Nonion depressulus (Walker and Jacob)

Original reference: *Nonion depressulus* (Walker and Jacob), 1798: p.641, pl.14, fig.33.
Recent reference: Haynes, 1973: p.209, pl.22, figs 8-11, pl.29, fig.9, text-fig.44 (1-3.)

Diagnosis: A near involute, compressed species of *Nonion* with narrow arched sutures heavily ornamented with tubercles towards the umbilicus.

Genus ***Nonionella*** Cushman, 1926

Nonionella turgida (Williamson)

Original reference: *Rotalina turgida* Williamson, 1858: p.50, pl.4, figs 95-97.
Recent reference: Haynes, 1973: p.213, pl.22, fig.12, text-fig.45 (4).

Diagnosis: A sub - globose species of *Nonionella* with deeply depressed sutures. The final chamber forms a flap over the umbilical region.

Family **ELPHIDIIDAE** Galloway, 1931

Genus ***Elphidium*** De Montfort, 1808

Elphidium crispum (Linné)

Original reference: Nautilus crispum Linné, 1758: p.709.
Recent reference: Murray, 1971: p.155, pl.64, figs 1-6.

Diagnosis: A keeled species of *Elphidium* with long, evenly spaced, retral processes spanning the sutures between the narrow chambers and a large umbilical boss. Spines originating from the periphery are occasionally seen.

Elphidium gerthi Van Voorthuysen

Original reference: Van Voorthuysen, 1957: p.32, pl.23, fig 12 a,b.
Recent reference: Murray, 1971: p.161, pl.67, figs 1-7.

Diagnosis: A compressed, slightly evolute species of *Elphidium* with deeply depressed sutures which are crossed by short retral processes.

Elphidium macellum (Fitchel and Moll)

Original reference: *Nautilaus macellum* Fitchel and Moll, 1798: p.66, var. ß pl.10, figs h-k.
Recent reference: Jones, 1994: p.109, pl.110.

Diagnosis: A highly compressed species of *Elphidium* with a slight keel and a flat umbilicus.

Elphidium margaritaceum (Cushman)

Original reference: *Elphidium advenum* (Cushman) var. *margaritaceum* Cushman, 1930: p.25, pl.10, fig.3.
Recent reference: Haynes, 1973: p.203, pl.24, figs 12, 13, pl.29, fig.8.

Diagnosis: A densely perforate, compressed species of *Elphidium* with an acute periphery.

Family **GLOBIGERINIDAE** Carpenter, Parker and Jones, 1862

Genus ***Globigerina*** d'Orbigny, 1826

Globigerina bulloides d'Orbigny

Original reference: d'Orbigny, 1826: p.277.
Recent reference: Loeblich and Tappan, 1988: p.489, pl.535, figs 1-7.

Diagnosis: A globose species of *Globigerina* with deep, distinct sutures.

Genus ***Orbulina*** d'Orbigny, 1839

Orbulina universa d'Orbigny

Original reference: d'Orbigny, 1839: p.3, pl.1, fig.1.
Recent reference: Haynes, 1973: p.184, pl.20, fig.6.

Diagnosis: A species of *Orbulina* with a final single chamber that encloses the trochospiral juvenille.

Superclass **RHIZOPODEA** Dujardin, 1835

Class **LOBOSIA** Carpenter, 1861

Order **ARCELLINIDA** Kent, 1880

Superfamily **Arcellacea** Ehrenberg, 1843

Family **Centropyxidae** Jung, 1942

Genus ***Centropyxis*** Jung, 1942

Centropyxis aculeata Ehrenberg

Original reference: Arcella aculeata Ehrenberg, 1832b: p.91.
Recent reference: Ogdon, 1980: p.46, pl.12, figs a-d.

Diagnosis: An ovoid species of *Centropyxis* with lateral spines and sub-terminal aperture.

Centropyxis discoides Penard

Original reference: ***Arcella discoides*** Penard, 1890: vol.31, p.150, pl.5, figs 38-41.
Recent reference: Ogdon, 1980: p.54, pl.16, figs a-e.

Diagnosis: A compressed, discoid species of *Centropyxis* with a terminal aperture.

Centropyxis ecornis Ehrenberg

Original reference: Arcella *ecornis* Ehrenberg, 1841: Deflandre, 1929: vol.67, p.359, text-figs 123-138.
Recent reference: Ogdon, 1980: p.56, pl.17, figs a-e

Diagnosis: A sub-round, tapering species of *Centropyxis* with a sub-terminal aperture.

Family **Difflugiidae** Wallich 1864

Genus ***Difflugia*** Leclerc, 1815

Difflugia acuminata Ehrenberg

Original reference: Ehrenberg, 1838: p.31, fig.3.
Recent reference:Ogdon, 1980: p.118, pl.48, figs a-c.

Diagnosis: An elongate, tubular species of *Difflugia* with a short spine at the base. The aperture is open and circular.

Difflugia avellana Penard, 1890

Original reference: Penard, 1890: vol.31, p.261.
Recent reference: Ogdon, 1980: p.120, pl.49, figs a-d.

Diagnosis: A slightly compressed, elongate species of *Difflugia* with an oval aperture.

Difflugia corona Wallich

Original reference: *Difflugia proteiformis* sub-sp. *globularis* var. *corona* Wallich, 1864: vol. II, p.241, pl. XIII: Archer, 1866: p.186.
Recent reference: Ogdon, 1980: p.128, pl.53, figs a-d.

Diagnosis: A spherical to ovoid species of *Diffllugia*, occasionally with spines on the aboral region. The aperture is circular and has a denticular collar.

Difflugia globulosa Dujardin

Original reference: Dujardin, 1837: p.30, figs 29, 30, pl.XV, figs 7, 8, pl.XVI.
Recent reference: Ogdon, 1980: p.134, pl.56, figs a-c.

Diagnosis: A simple, globular species of *Difflugia*.

Difflugia labiosa Wailes

Original reference: *Difflugia amphora* Wailes, 1919: 1902: p.39, pl.15, fig.11.
Recent reference: Ogdon, 1980: p.138, pl.58, figs a-c.

Diagnosis: An oval species of *Difflugia.* The aperture has a shallow collar with an undulating rim.

Difflugia lithophila Penard

Original reference: Penard, 1902: p.714.
Recent reference: Ogdon, 1980: p.142, pl.60, figs a-c.

Diagnosis: A simple, ovoid species of *Difflugia* with a moderately raised collar.

Difflugia urceolata Carter

Original reference: Carter, 1864: p.27, pl.1, fig.7.
Recent reference: Medoili and Scott, 1983: p.31, pl.3, figs 1-3, pl.4, figs 1-4.

Diagnosis: A circular to ovoid species of *Difflugia* with short aboral protuberances. The aperture is surrounded by an apical rim which is curled outwards.

Difflugia viscidula Penard

Original reference: Penard, 1902: p.259, text-fig.
Recent reference: Ogdon, 1980: p.160, pl.69, figs a-d.

Diagnosis: A simple, ovoid species of *Difflugia*.

Pontigulasia compressa Carter

Original reference: Difflugia compressa Carter, 1864: p.22, pl.1, figs 5, 6.
Recent reference: Ogdon, 1980: p.162, pl.70, figs a-d.

Diagnosis: An elongate species of *Difflugia* with a tapered neck.

Pseudodifflugia gracilis Schlumberger

Original reference: Schlumberger 1845: p.245, 3.
Recent reference: Ogdon, 1980: p.174, pl.76, figs a-c.

Diagnosis: A squat, circular species of *Pseudodifflugia*.

Species	RC	F	A	E
Amphicoryna cf. *A. scalaris* (Batsch, 1791)	X	X	R	R
Astacolus crepidulus (Fichtel and Moll, 1798)	X	X	R	R
Asterigerinata mamilla (Williamson, 1858)	O	O	C	C
Bolivina pseudoplicata Heron-Allen and Earland 1930	O	O	C	C
Brizalina cf. *B. pseudopunctata* (Höglund, 1947)	O	O	C	C
Brizalina spathulata (Williamson,1858)	O	R	C	C
Brizalina variabilis (Williamson, 1858)	O	R	C	C
Buccella frigida (Cushman, 1921)	O	X	O	O
Buliminella elegantissima d'Orbigny 1839	X	X	O	R
Bulimina gibba Farnasini 1902	O	R	O	O
Bulimina marginata d'Orbigny 1826	O	R	O	O
Cancris auricula (Fichtel and Moll, 1798)	X	X	R	R
Cassidulina obtusa Williamson 1858	X	X	O	R
Cibicides lobatulus (Walker and Jacob, 1798)	C	O	A	A
Cornuspira foliacea (Philippi, 1844)	X	X	R	R
Cyclogyra involvens (Reuss, 1850)	O	R	O	O
Eggerelloides scabra (Williamson,1858)	O	C	R	R
Elphidium crispum (Linné, 1758)	C	O	C	C
Elphidium gerthi Van Voorthuysen 1957	O	R	R	R
Elphidium macellum (Fitchel and Moll, 1798)	C	O	C	C
Elphidium margaritaceum (Cushman, 1930)	O	R	O	O
Fissurina lagenoides (Williamson, 1848)	O	X	R	R
Fissurina lucida (Williamson, 1848)	O	R	C	C
Fissurina marginata (Montagu, 1803)	O	R	C	C
Fissurina orbignyana Seguenza 1862	O	O	C	C
Glabratella milletti (Wright, 1911)	C	R	C	C
Gavelinopsis praegeri (Heron-Allen and Earland, 1913)	C	R	C	C
Glandulina ovula d'Orbigny 1846	X	X	R	R
Globigerina bulloides d'Orbigny 1826	X	X	R	R
Globulina gibba d'Orbigny 1826	X	R	O	O
Globulina d'Obigny var. *myristiformis* (Williamson, 1858)	X	X	R	R
Globocassidulina aff. G. *subglobosa* (Brady, 1881)	X	X	R	R
Guttulina lactea (Walker and Jacob, 1798)	X	R	C	C
Haplophragmoides wilberti Anderson 1953	X	C	C	C
Lagena clavata (d'Orbigny, 1846)	R	R	O	O
Lagena interrupta Williamson 1848	R	R	C	C
Lagena laevis (Montagu, 1803)	R	R	C	C
Lagena perlucida (Montagu, 1803)	X	X	O	O
Lagena semistriata Williamson 1848	O	R	C	C
Lagena substriata Williamson 1848	O	R	C	C
Lagena sulcata (Walker and Jacob, 1798)	O	R	C	C
Lagena tenuis (Bornemann, 1855)	R	R	O	O
Lamarckina haliotidea (Heron-Allen and Earland, 1911)	X	X	R	R
Lenticulina peregrina (Schwager, 1866)	X	R	O	R
Massilina secans (d'Orbigny, 1826)	O	X	O	O

Cont.....

Species	RC	F	A	E
Nonion depressulus (Walker and Jacob, 1798)	O	O	C	C
Nonionella turgida (Williamson, 1858)	X	X	R	R
Oolina hexagona (Williamson, 1858)	R	R	O	O
Oolina lineata (Williamson, 1858)	R	X	O	R
Oolina melo d'Orbigny 1839	R	X	O	R
Oolina squamosa (Montagu, 1803)	R	X	R	R
Oolina williamsoni (Alcock, 1865)	O	R	O	O
Orbulina universa d'Orbigny 1839	X	R	R	R
Parafissurina malcomsoni (Wright, 1911)	R	X	R	R
Patellina corrugata Williamson 1858	O	O	O	O
Pateoris hauerinoides (Rhumbler, 1936)	X	X	R	R
Planorbulina mediterranensis d'Orbigny 1826	R	R	C	C
Procerolagena gracilis (Williamson, 1848)	X	X	R	R
Prygo depressa (d'Orbigny, 1826)	X	X	R	X
Quinqueloculina bicornis (Walker and Jacob) var. *angulata* (Williamson, 1858)	X	R	R	X
Quinqueloculina dimidiata Terquem 1876	R	C	C	C
Quinqueloculina lata Trequem 1876	C	C	C	C
Quinqueloculina oblonga (Montagu, 1803)	R	X	O	O
Quinqueloculina semimulum (Linné, 1758)	X	R	O	O
Reophax moniliformis Siddall 1886	X	C	O	C
Rosalina anomala Terquem 1875	O	O	C	C
Rosalina williamsoni (Chapman and Parr, 1958)	R	O	C	C
Spirillina vivipara Ehrenberg 1843	R	X	R	R
Spiroloculina excavata d'Orbigny 1846	X	X	R	R
Stainforthia fusiformis (Williamson, 1858)	O	R	C	C
Trochammina ochracea (Williamson, 1858)	O	C	C	C
Trochammina rotaliformis Heron-Allen and Earland 1911	O	O	C	C
Centropyxis aculeata Ehrenberg 1832	O	X	O	O
Centropyxis discoides Penard, 1890	O	X	O	O
Centropyxis ecornis Ehrenberg 1841	R	X	O	O
Difflugia acuminata Ehrenberg, 1838	X	X	R	R
Difflugia avellana Penard, 1890	X	X	R	R
Difflugia corona Wallich, 1864	X	X	R	R
Difflugia globulosa Dujardin, 1837	X	O	O	O
Difflugia labiosa Wailes, 1919	R	O	O	O
Difflugia lithophila Penard, 1902	X	R	O	O
Difflugia urceolata Carter, 1864	X	R	O	O
Difflugia viscidula Penard, 1902	X	X	R	R
Pontigulasia compressa Carter, 1864	X	C	O	O

Table 3.1. Transported-in species. The categories used indicate relative abundance with reference to that estuary alone and do not represent relative abundaces between locations. Abbreviations are as follows: RC - Restronguet Creek, F - Fowey, A - Avon, E - Erme, A - abundant (>50%), C - commonly found in most samples (<20%), O - occasional appearance in some samples (<5%), R - rare appearance (<1%) and X - none found.

Chapter Four

Environmental Background Data

4.1 Introduction

The environmental background data includes information on local climatic conditions, the abiotic variables (salinity and temperature), metal concentrations in the sediments, sediment grain size analysis and mineralogy, organic carbon, nitrogen and the carbon-nitrogen (C/N) ratio. The water quality data (metal concentration and pH) were provided by the Environment Agency's systematic monitoring programme, but these data are only available for Restronguet Creek. Information (1991 - 1996) is given here only for the Devoran road bridge monitoring station (Figure 1.3) because it is outside the area affected by tidal water intrusion; tidal effects can account for significant variation in chemical speciation and partitioning behaviour (Chester, 1990; Boyden *et al.*, 1979). Only broad use is made of data obtained from the 'fixed' monitoring station at the mouth of the Creek (off Pandora Inn) as it has not always been sited in the same position and occasionally has been absent.

4.2 Local climate

4.2.1 Introduction

The climatic data given here covers the period from the closure of Wheal Jane tin mine onwards (1991 - 1996). The seasonal windspeed and direction, rainfall and atmospheric temperature were obtained from a number of sources; personal field measurements, the meteorlogical records for Plymouth City (data stored using Metenq. 4.1 software) and from a local recording station in Falmouth (courtesy of K.W.Bryan).

4.2.2 Windspeed and direction

Windspeed varied from 1 to 35 knots. The highest winds were recorded in the winter months (December, January and February); summer windspeeds did not exceed 17 knots and generally being below 9 knots. Usually, strongest winds were from the south and south west (180-260°) and were occasionally very destructive (January, 1990 and 1998).

4.2.3 Rainfall

Monthly rainfall varied between 0 - 214mm each day for the year. The winter months (December - March) had a daily range between 0 - 214mm and summer between 0 - 184mm (June - August). Whilst daily rainfall for the spring and autumn varied between 6 - 135mm. The data show that the monthly rainfall recorded in the winter and summer can be more equitable than expected and this is a regional trend due to the warmer climate which prevails in the south west of England. However, there are more days recording zero rainfall in the summer months relative to the winter.

High (214mm) and prolonged periods of rainfall (weekly and monthly) are exceptional and in January 1995, for example, both red and amber flood warnings were issued by the Environment Agency. The sample stations C19, K20 and H23 (Figure 1.14) remained flooded at low tide during this time. Prolonged periods of zero rainfall are similarly exceptional and have led to drought conditions. In the summer of 1995, for example, no rainfall was recorded in June, July and August, which resulted in the river channel and reservoir storage being reduced to levels not previously recorded.

4.2.4 Atmospheric temperature

Air temperature differs markedly between summer and winter. The summer ranged between 7.7 and 32 °C (the higher value recorded in July 1995). The winter ranged between -15 and 14.4°C (-15°C was recorded in January 1996 and probably reflects the additional influence of wind chill). Spring and autumn values are more equitable and range between 5 and 16.7°C.

4.3 Salinity and temperature

4.3.1 Introduction

Salinity and water temperature are known to affect both foraminiferal ecology and species distribution and the fate of dissolved metals in solution which are more toxic at lower salinities (Bryan and Langston, 1992; Depledge, 1990; M^cLusky *et al.*, 1986). Salinity (‰ - parts per thousand) is regarded as one of the factors which limits colonisation by certain foraminiferal species (Phlegler, 1960, 1970; Hansen, 1965; Lee *et al.*, 1969; Matera and Lee, 1972; Murray, 1973, 1991; Hart and Thompson, 1974; Lee, 1974; Scott and Leckie, 1990; Scott *et al.*, 1991; Alve, 1995a; DeRijk, 1995, 1996). Salinity stress (high or low salinity) affects the behaviour of organisms, especially those whose tolerance ranges are limited and can adversely influence reproduction and induce morphological variation (Lidz, 1965; Müller, 1975; Poag, 1978; M^cLusky, 1989; Amolgi-Labin, *et al.,* 1992; Chang and Kaesler, 1974). However, estuarine foraminiferal species are generally brackish water organisms with a salinity tolerance range of 5-18‰.

Salinity gradients may be used to separate an estuary into physical abiotic zones (Buzas, 1969; Setty, 1984; M^cLusky, 1989; Patterson, 1990) and a scheme similar to that proposed by M^cLusky (1989) is used here. The salinity range of <5‰ defines the head of the estuary, >5-<18‰ defines the upper estuary, >18-<25‰ the mid estuary and the lower estuary or reaches has a range of >25-<30‰. The marine saline waters of >30‰ are encountered at the mouth of an estuary (M^cLusky, 1989).

Temperature is an important parameter in foraminiferal ecology and is considered to control productivity and rates of survival (Parker and Athearn, 1959; Phlaegler, 1960; Arnal, 1955; Bradshaw, 1961; Lidz, 1965; Greiner, 1969; Müller, 1975; Schnitker, 1974; Ellison, 1984; Angell, 1990). Temperature has also been demonstrated to influence test morphology and to determine the dominant morphotype; e.g., *Ammonia beccarii* instead of *A. tepida* (Lidz, 1965; Chang and Kaesler, 1974; Alve, 1995).

With respect to metals, the temperatures encountered in UK estuaries are not considered to have a significant effect upon the behaviour of metals in solution (Bryan and Langston, 1992). The daily exposure of the mudflats to variable degrees of solar radiation, however, may affect metal availability, particularly if the level of ultra-violet radiation is increasing (Hallock *et al.*, 1995; Hatch and Burton, 1998; Kosian *et al.*, 1998).

4.3.2 Seasonal salinity data

In all the estuaries studied salinity readings were taken from the shore at mid to low depths in shallow water and detected no stratification. However, boat surveys carried out in deeper water (1.5 - 12m depth) did detect weak stratification (Stubbles, 1995) and, therefore, both the control estuaries and Restronguet Creek are regarded as partially stratified/mixed.

Figure 4.1 represents seasonal data for Restronguet Creek and was obtained over a five year period and averaged to reduce the data to four seasonal sets. Figures 4.2 - 4.4 show the data obtained for each season over one year for each control estuary. The data sets, therefore, give both spatial and temporal information.

Restronguet Creek has a salinity range of 0-35‰ (from above the maximum tidal limit) which takes the upper range above the tolerance limits for most brackish water organisms, c.25‰.

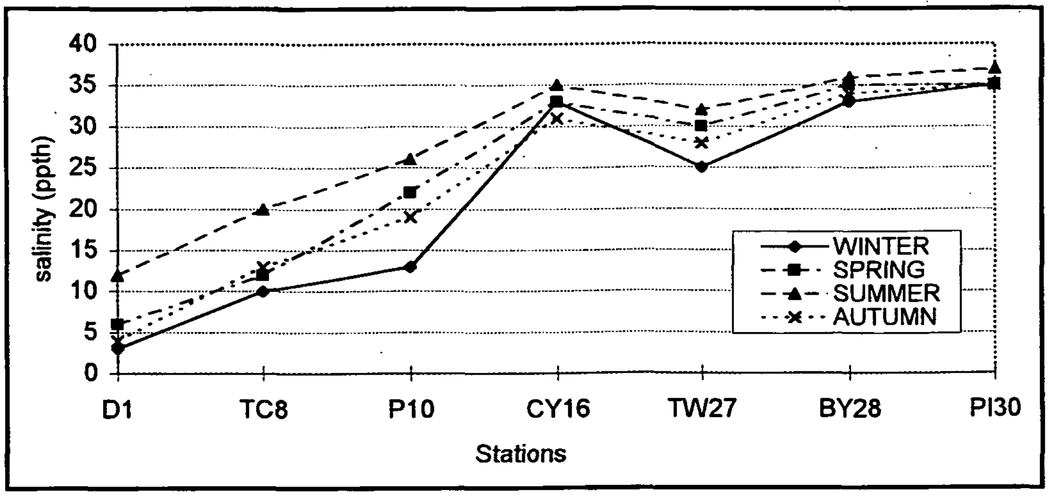


Figure 4.1: Salinity gradient, Restronguet Creek.

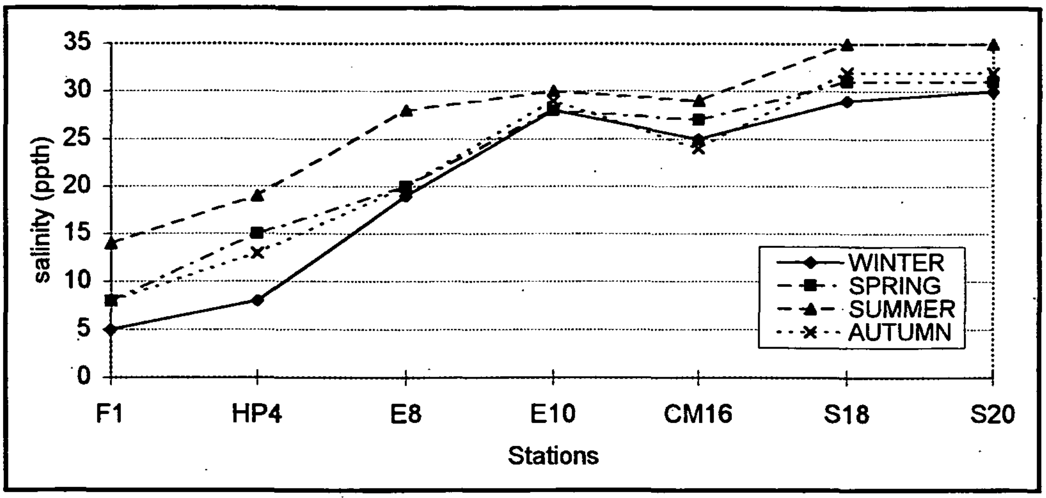


Figure 4.2: Salinity gradient, Erme Estuary.

The salinity profiles show an increase down each estuary and Restronguet Creek which in all cases are higher in the summer and lower in the winter. This is particularly pronounced with respect to sample station A2 (Avon, 1995 - 1996). The winter and summer survey periods coincided with unusual weather conditions which affect the amount of channel flow (Section 4.2) and the channel narrows at this point which may affect mixing processes between the tidal and fresh water.

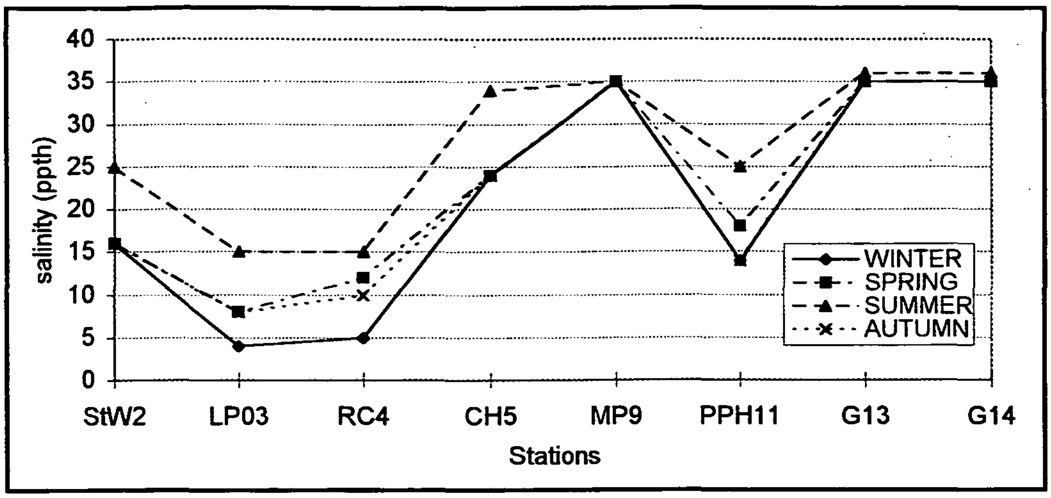


Figure 4.3: Salinity gradient, Fowey Estuary.

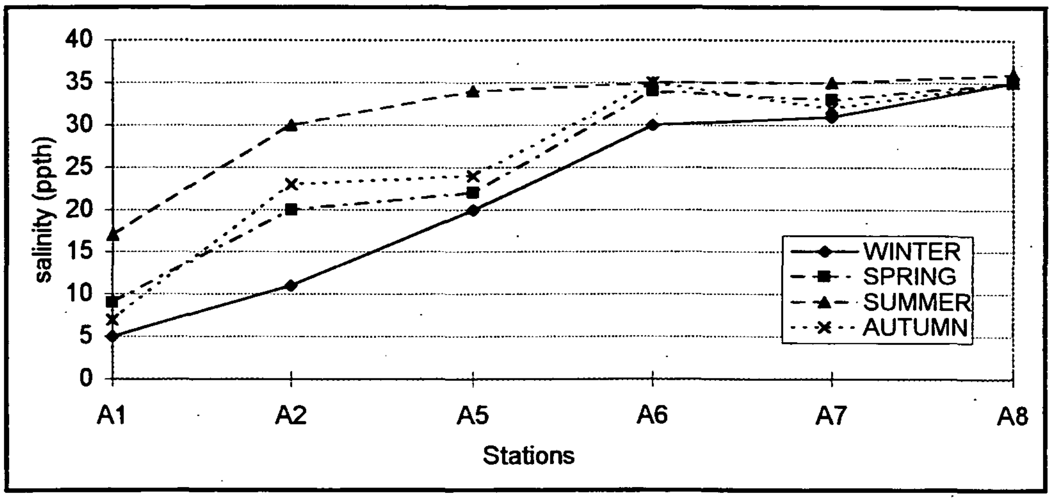


Figure 4.4: Salinity gradient, Avon Estuary.

The profile in the Fowey Estuary is highly variable and reflects the salinity levels at the subsidiary creek stations LP03, RC4 and PPH11 were routinely lower than the stations in the main channel. This may reflect the effects of silting up and distance from the main channel which is dredged at Fowey.

4.3.3 Salinity zonation

The stations in each estuary can be classified on the basis of the scheme outlined above (Section 4.3.1) and Tables 4.1 and 4.2 show this arrangement. Only one or two stations from each location are within the head of estuary zone (D1, F1, LP03, RC4 and A1) and none fall into this category in the summer when there is a general shift to higher salinities. Of the other three zones the lower estuary is the largest group, having the highest number of sample stations. The foraminiferal (Chapter Five) data show that the typical estuarine species (tolerance 5-18‰) are present at locations which extend above and below this range and these species should, therefore, be more accurately described as euryhaline, having an additional upper range of 18-25‰ (Murray, 1991).

Area of Estuary	Restronguet Creek	Erme	Fowey	Avon
Head of estuary <5‰	D1	F1	LPO3,RC4	A1
Upper estuary ≥5-18‰	TC8,P10	HP4,E8	StW2,PPH11	A2
Mid estuary ≥18-25‰	TW27	CM16	CH5	A5
Lower estuary ≥25-35‰	CY16,BY28, PI30	E10,S18, S20	MP9,G13,G14	A6,A7,A8

Table 4.1: Zonation in winter salinity zones.

The control estuary and Creek sample stations upstream of the mouth (c. 0.25 - 1km) consistently recorded salinity values up to 35‰. For this research, therefore, the zonation of the lower reaches has been revised, the two lower zones used by M[c]Lusky (1989) being united into a single zone having a range of >25-35‰.

Area of Estuary	Restronguet Creek	Erme	Fowey	Avon
Head of estuary <5‰				
Upper estuary ≥5-18‰	D1	F1	LPO3,RC4,	A1
Mid estuary ≥18-25‰	TC8,P10	HP4	StW2,PPH11, CH5	
Lower estuary ≥25-35‰	CY16, TW27, BY28,PI30	E8,CM16, E10,S18, S20	MP9,G13,G14	A2,A5,A6,A7, A8

Table 4.2: Zonation in summer salinity.

4.3.4 Pore water salinity

While there were substantial differences between some readings due to problems in sampling technique (Chapter Two, Section 2.1.1) the obtained data do give a general indication of the variation in pore water salinity with distance down each estuary and Restonguet Creek. As with the surface samples, the pore water chemistry is influenced by evaporation and freshwater run-off, particularly as the samples taken were from the very top centimetre of oxidised sediment.

Pore water salinity in Restronguet Creek varies between 10 and 44‰ in the summer and 5 and 36‰ in the winter, with the lower values recorded at stations D1, C19 and K20, and the highest at stations P10, CY16, BY28 and PI30. The occasional high values (44‰) may be due to the evaporation of residual tidal water. Field observations support this as it was evident that the glassy sheen on the sediment surface at low tide was a tidal water film which remained throughout the low tidal cycle, even in the summer.

The control estuaries Erme and Avon had similar pore water salinity gradients. In the winter the upper estuary stations F1 (Erme Estuary) and A1 (Avon Estuary) have values below 3‰ but in the summer this rises to 9 and 13‰ respectively. The lower estuary stations E10 and S20 (Erme Estuary), A8 and A12 (Avon Estuary), had the highest salinities at 35‰ in the winter and 40‰ in the summer.

Fowey Estuary generally had slightly higher salinities for all seasons, and the upper estuary stations StW1 and 2 had salinities of 8‰ in the winter and 22‰ in the summer. The upper creek stations LPO3 and RC4 had slightly lower salinities of 1‰ in the winter and 5‰ and 12‰ respectively in the summer. The lower estuary stations MP9, MP10, G12, G13 and G14 had a stable profile showing least variation and varied between 36‰ in the winter and 39‰ in the summer. Each of the control estuaries appeared to drain well at low tide and, unlike Restronguet Creek, there was no long lasting residual water film.

4.3.5 Summary

In summary, the data show that salinity is highly variable. This is caused by the changing nature of freshwater flow, the amount of residual flood tidal water and evaporation brought about by solar radiation (Haynes and Dobson, 1969). At the local level, freshwater springs and run-off will further dilute the incoming tidal waters (Alve, 1995a; DeRijk, 1996). Clearly, such wide salinity ranges have implications as to which foraminiferal species will tolerate such variable environmental conditions and will affect diversity (Phlegler, 1965; Greiner, 1969; Boltovskoy and Lena, 1971; Boltovskoy and Wright, 1976; DeRijk, 1995; Stubbles, 1995; Stubbles, *et al.,* 1996a,b).

4.3.6 Seasonal temperature data

The shallow water surveys did not detect vertical temperature variation below the top 10cm but thermal stratification was found during the boat surveys. The upper 10cm column of water is affected by solar radiation and the temperatures are some 3°C warmer than the deeper water. Spatial temperature gradients and temporal variation are evident for Restronguet Creek and each estuary (Figures 4.5 - 4.8). The lowest mean temperatures (1-13°C) were recorded at the head of each control estuary and Restronguet Creek and the highest (6 - 18°C) in the lower reaches. The lowest seasonal temperatures were recorded in the winter (min. 1°C), with the highest in the summer (max. 22°C).

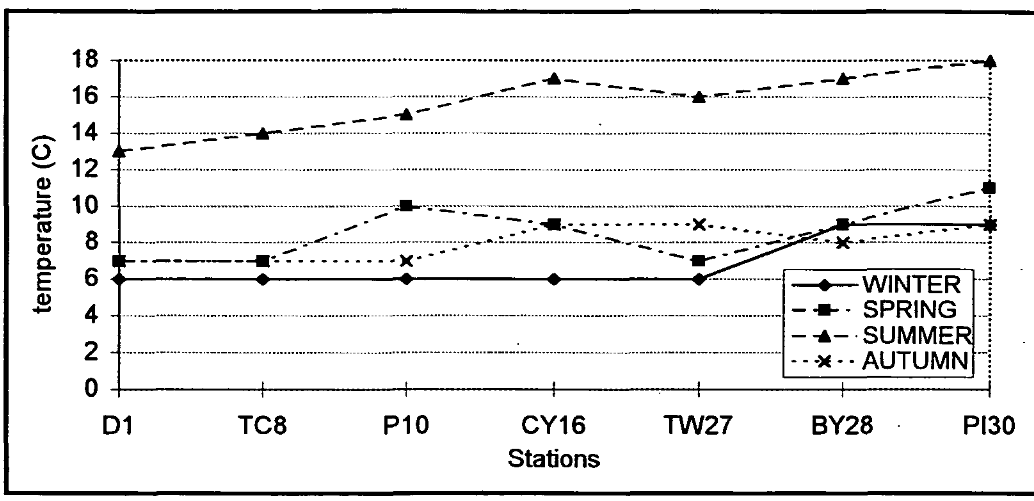


Figure 4.5: Temperature gradient, Restronguet Creek.

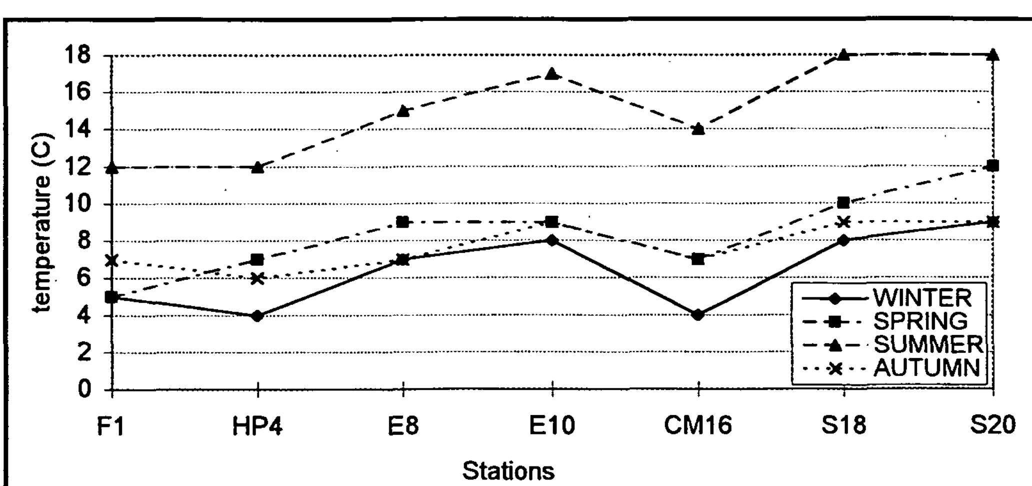


Figure 4.6: Temperature gradient, Erme Estuary.

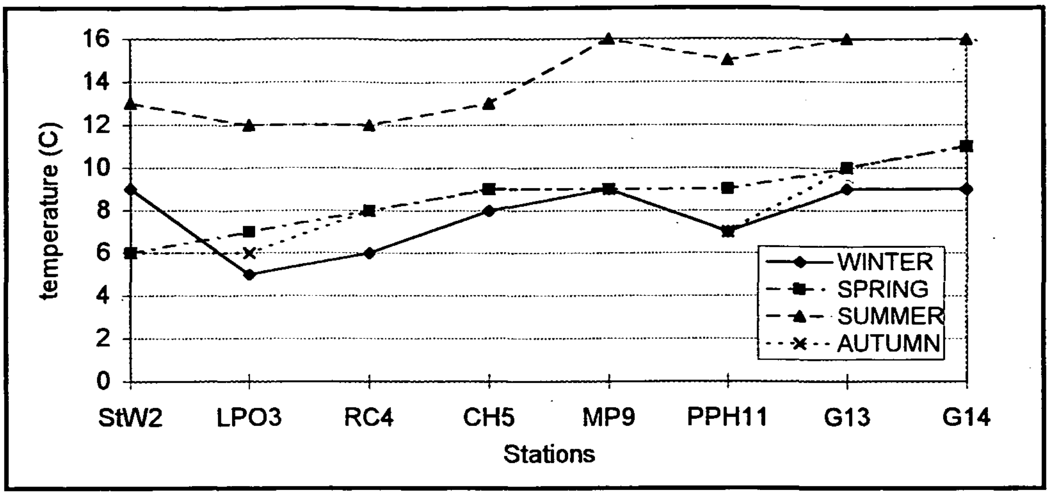


Figure 4.7: Temperature gradient, Fowey Estuary.

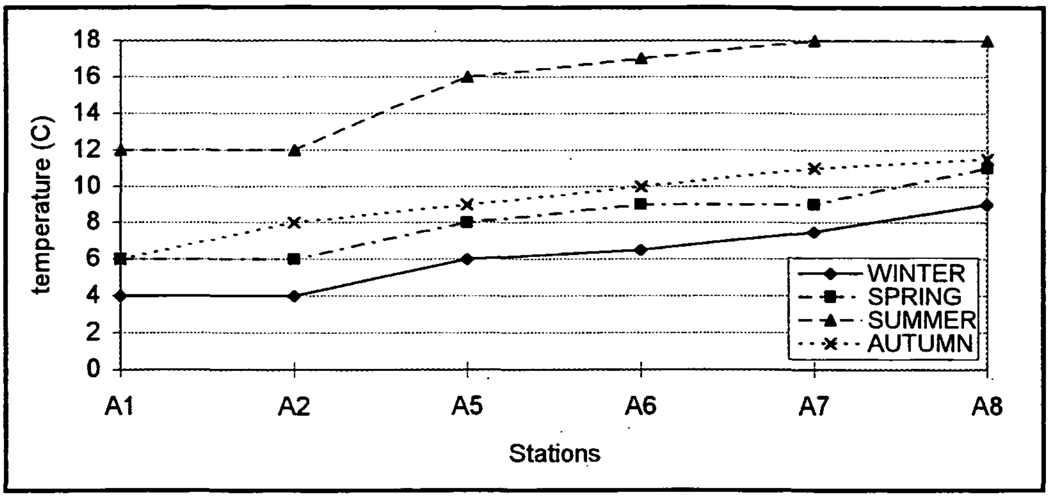


Figure 4.8: Temperature gradient, Avon Estuary.

The summer 1995 data provided the highest temperatures when channel water flow and depth of water were unusually low for about 4 months. The lowest temperatures were recorded in January 1996 when daytime air temperatures were below freezing for a month. It was also found that the difference in temperature between the channel water (cooler) and the incoming tidal waters (warmer) was more pronounced in the winter relative to the summer.

4.3.7 Summary

The high variation in temperature can be accounted for by a number of reasons, individually or in combination, as follows:

- Non-equilibrium mixing between the cooler fresh channel water and incoming seawater;
- Variable river channel water depth, affecting mixing between sea and channel water;
- Variable river channel flow. Low flow, for example, will disturb the summer thermocline least, enabling it to rise higher up the estuary;
- Additional freshwater flow from other sources, for example, rainwater run-off, rivulets and springs, and
- Solar heating of the exposed mudflats, followed by heat transfer processes.

4.4 Sediment grain size and mineralogy

4.4.1 Introduction

The sediment grain size distribution and the types of minerals available may also affect foraminiferal species distribution, particularly the effect these parameters may have in restricting the distribution of the agglutinated species. The most obvious limitation would be the maximum size of the organism and the availability of a suitable size range of particles needed during development. Colonisation by foraminifera (both calcareous and agglutinated species) is also affected by high proportions of coarse clastic material as this infers high water velocities which makes stable colonisation less likely to occur (Murray, 1991). Matera and Lee (1972) noted that both calcareous and agglutinated species cluster around specific median grain sizes, indicating preferential colonisation. *Elphidium williamsoni* (as *Elphidium incertum*) clustered around material with a median grain size of 0.1mm but *Trochammina inflata* clustered around a median grain size of 0.46mm. Preference for muddy sediments has also been established because they contain higher proportions of organic matter (a food source for foraminifera) relative to sand (Lidz, 1965; Buzas *et al*, 1989; Warwick *et al.*, 1995).

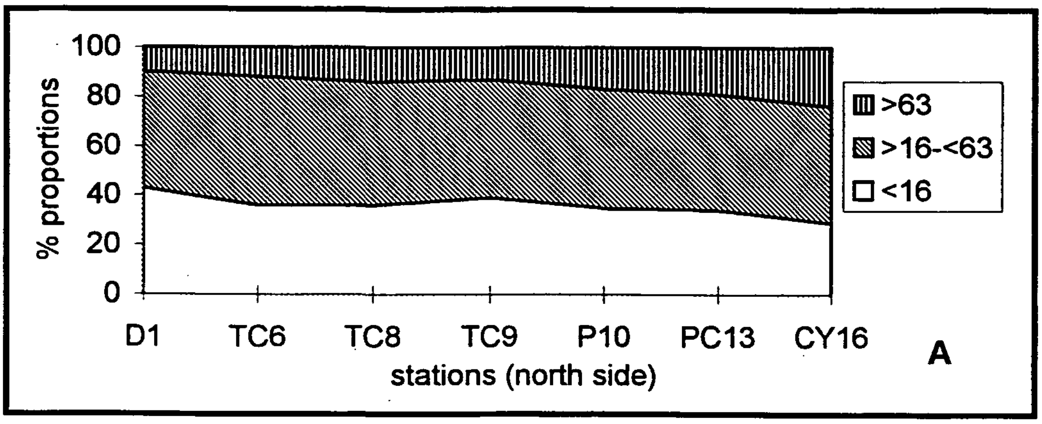
The proportion of silt, and particularly clay (<63 µm), can also affect the concentration of sediment-bound metals by the process of adsorption-desorption and has been shown to account for the variation between sample locations (Chester and Stoner, 1975; De Groot and Allersma, 1975; Luoma and Bryan, 1981; Salomans and Förstner, 1984; Langston, 1986; Horowitz *et al.*, 1990; Davidson *et al.*, 1994; Attrill and Thomas, 1995). This very complex physico-chemical relationship is an important consideration when comparing metal concentrations between samples (as storage capacity) and potential metal availability (strength of ionic attraction and exchange capacity) to an organism (Chester and Stour, 1975). The fine fraction, <63 µm, is also more likely to be transported in the water column and the adsorbed metals are, therefore, in a higher state of bioavailablity (Salomons and Förstner, 1984). However, in areas of higher salinity (towards the mouth of an estuary), fine material forms flocculated colloids which tend to settle out of the water column and this reduces metal availability (Gardner, 1974; Sholkovitz, 1976).

The percentage proportions of each size fraction have been grouped, as follows: <16µm, <63µm and ≥63µm, (as a percentage proportion). Each category reflects a particular influence, for example, the average size required as agglutinating material (Chapter Five, Section 5.7), determined by SEM analysis of *Miliammina fusca*, *Jadammina macrescens* and *Trochammina inflata* (<16µm) and the preferential concentration of metals (<63µm).

4.4.2 Sediment grain size distribution

***i)* Restronguet Creek**

The highest proportions of fine (<63µm) material occur in sediment samples taken from Restronguet Creek (Figure 4.9, a and b) with a mean distribution of 86.6% in a range of 59 - 91%. The upper Creek samples D1 and C19 have a high proportion of fines >90% relative to the other stations in the Creek and the baseline/control estuaries. The majority of the samples, however, have a range of between 83 - 89% fine material. The Creek stations BY28 and H23 have a lower percentage proportion of fines, 58.6% and 52% (1993) respectively.



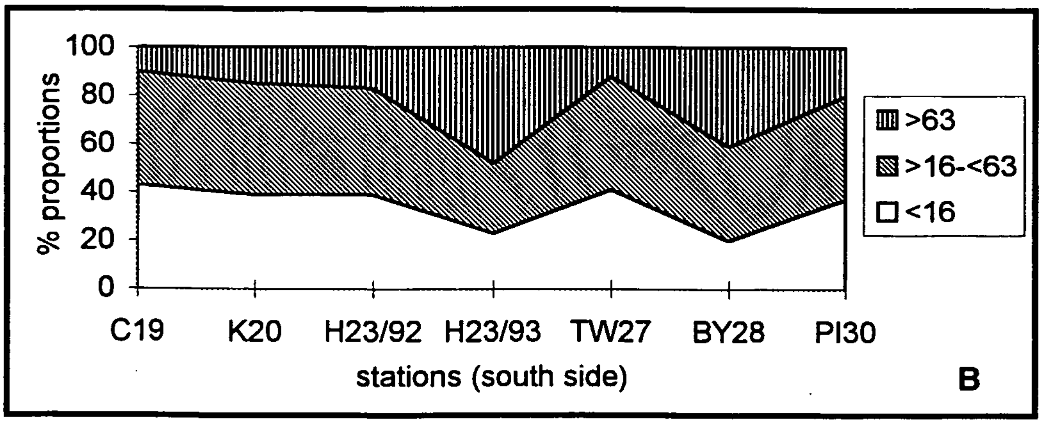


Figure 4.9: Sediment grain size distribution, Restronguet Creek. a) north side and b) south side.

Two samples from station H23 taken in 1992 and 1993 were analysed because the site was contaminated by predominantly iron coated quartz mine waste originating from the vicinity of the abandoned Restronguet Stream Tin Mine (Chapter One, Figure 1.6). Following inclusion of this coarser material the relative proportion of fines has been reduced to 52% while before inclusion it was 83%. The graphical mean particle size ranges from 16 - 24µm which is very fine and the narrowness of the range suggests that there is little variation between the samples.

Material in the grain size range <16µm is present in all samples, but the percentage proportions vary. Restronguet Creek (Figure 4.9, a and b) has the highest proportion below 16µm with a mean of 28% in a range of 20 - 48%.

***ii)* The Erme Estuary**

The grain size analysis for the Erme Estuary (Figure 4.10, a and b) demonstrates a greater proportion of fine and medium sand size material (≥63µm) relative to samples from the Fowey Estuary and Restronguet Creek. The mean percentage proportion of material <63µm is 55.6% in a range of 30 - 70%. Sample station S20, for example, has the lowest proportion of fines (<63µm), 29% but station CM17 has the highest with 72.7%. The sample group, HP2, OW12 and OW14 have a range of 50 - 55%. Stations HP3, HP4, E7, E10, OW11 and OW15 range between 40 - 49% while sample stations F1, E5, E6, E8, E9, CM16, S18 and S19 have lower values ranging from 31% - 39% fine material (Figure 4.10, a and b). Overall, the west side of the estuary has least variation relative to the east side (Figure 4.10a).

The graphical mean particle size is 28 - 125µm, indicating wide variation between the samples. Hence, the Erme samples have least silt and clay (<16µm), with a mean of 15% in a range of 9 - 31%.

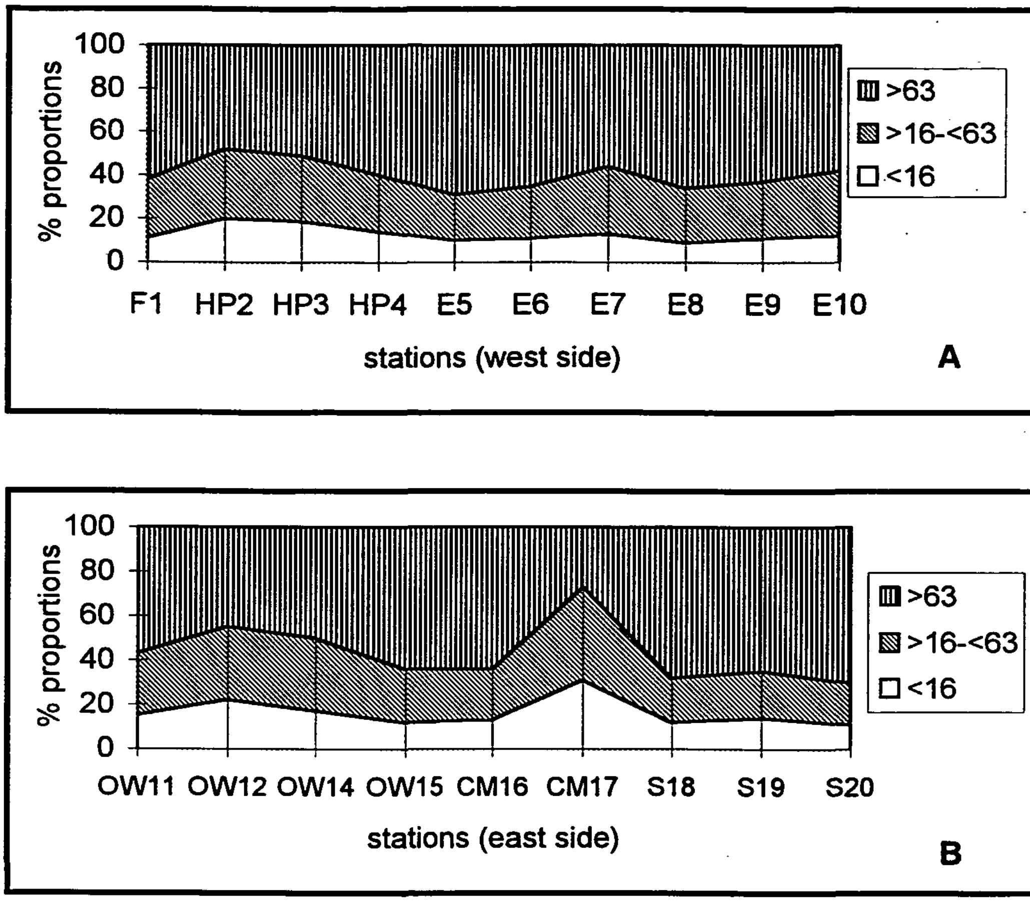


Figure 4.10: Sediment grain size distribution, Erme Estuary, a) west side and b) the east side.

***iii)* The Fowey Estuary**

Of the control estuaries, samples taken from the Fowey Estuary and it's subsidary creeks Lerryn and Pont (Figure 4.11, a and b) show the highest proportion of total fines but none exceed 80%. The mean percentage proportion below 63µm is almost 69%, in a range of 56 - 80%.

Sample stations StW1, 2, RC4, CH5, G12, G13 and G14 are between 70 and 80%. Samples from stations LPO3, MP9 and MP10 have between 60 and 69% (material <63µm). Those sample stations with <60% fine material are CH6 and PPH11.

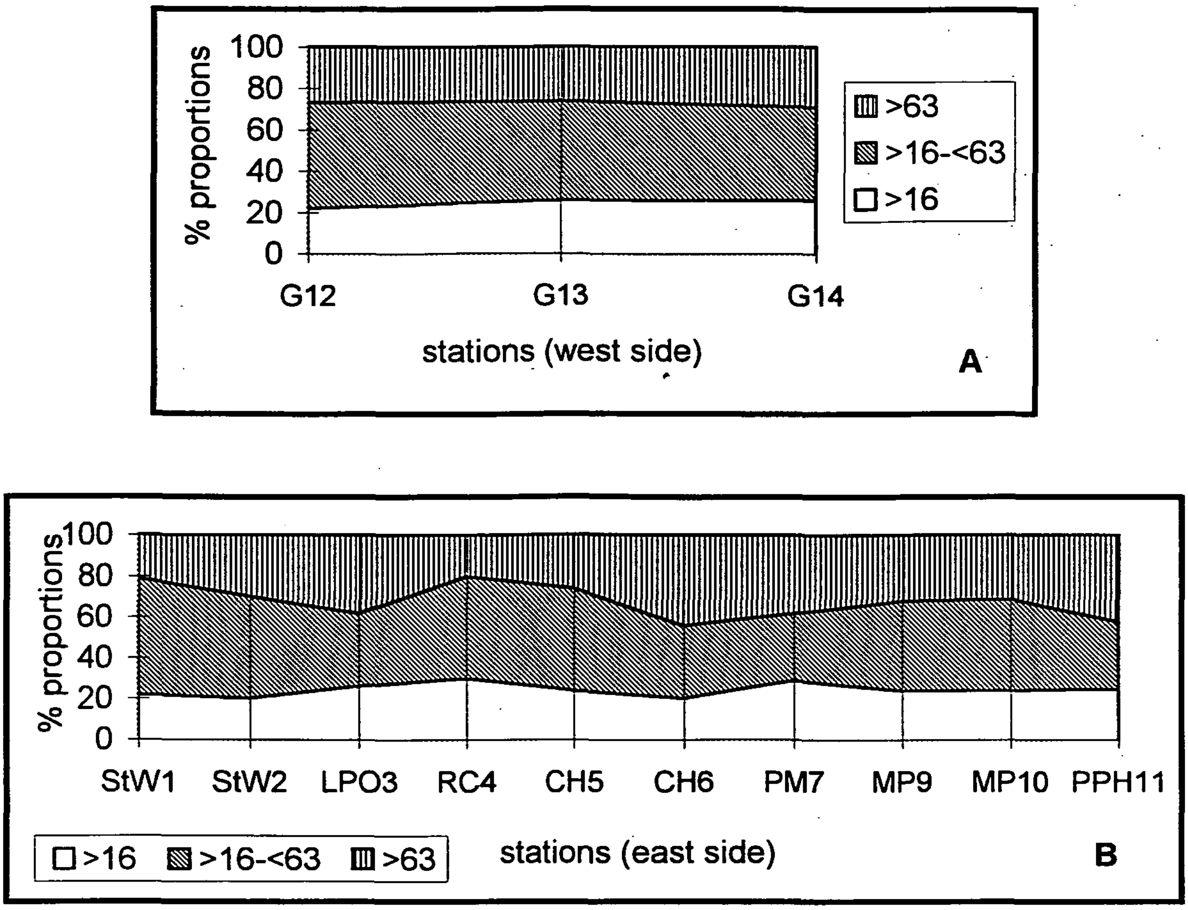
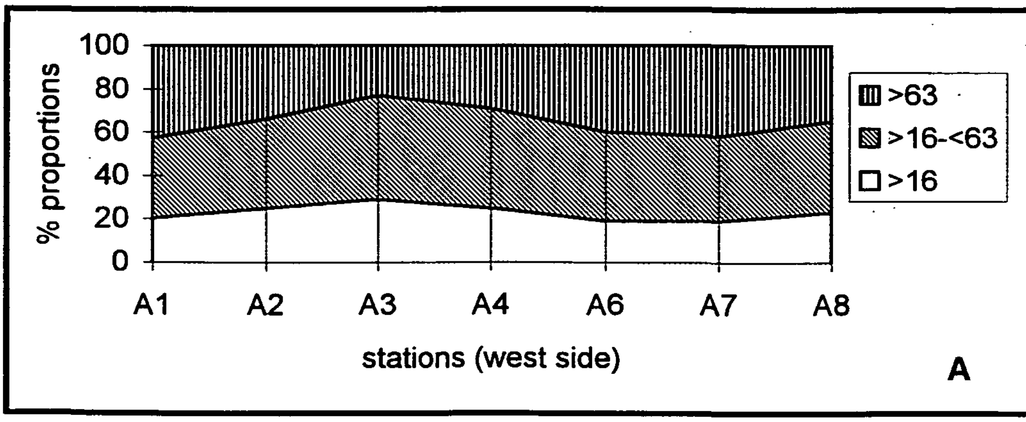


Figure 4.11: Sediment grain size distribution, Fowey Estuary, a) west side and b) the east side.

The graphical mean particle size range for Fowey is from 32 to 50µm which indicates low variation between the samples. The proportion of material <16µm is intermediate between Restronguet Creek and the Avon and Erme estuaries with a mean of 24.5% in a narrow range of 20 - 30%.

iv) The Avon Estuary

The grain size distribution in sediments from the Avon Estuary is similar to that of the Erme with a 60% mean proportion of <63µm material in a range of 42 - 77%. The highest proportions of fines (<63µm) are found in the sample group A3, A4 and A11 (70 - 77%) which are areas of mudfalt within the saltmarsh (Figure 4.12, a and b).



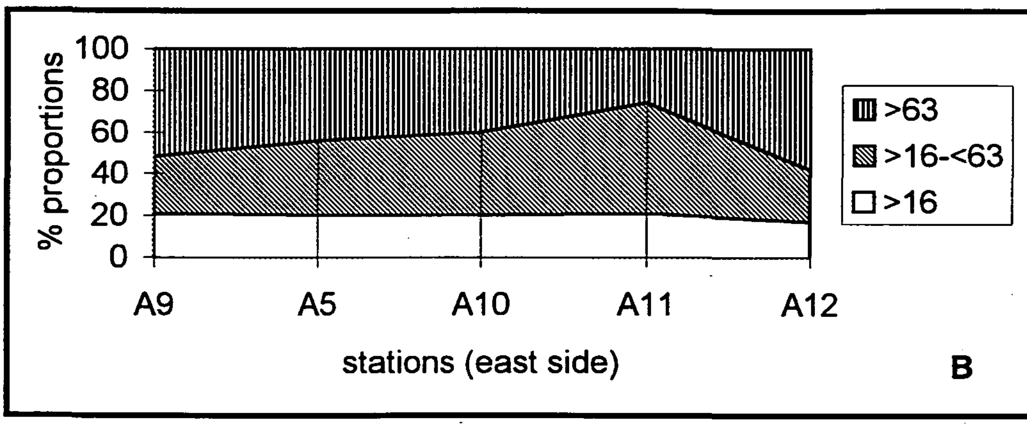


Figure 4.12: Sediment grain size distribution, Avon Estuary. a) west side and b) east side.

Samples A2 and A8 have similar values of c.65%. Samples A1, A5, A6, A7 and A10 (A10 is close to a storm drain) have a range of 57 - 60%. The sample group A9 and A12, which were taken from channel bars, have the lowest proportion of material with grain size <63µm, with values of 47.5% and 42% respectively (Figure 4.12, b). The graphic particle size range is 28 - 50µm which is similar to that for the Fowey samples, indicating low variation between the samples. The Avon has slightly higher proportions of material <16µm relative to the Erme Estuary with a mean of 21.6% in a range of 17 - 29%.

4.4.3 Summary

In general, the samples with the highest proportion of fine and medium sand size material (≥63μm) are either in close proximity to the river channel (stations: A9, F1, E5, E6, E8, E9, CH6 and PPH11) or the mouth of the estuary (stations: A12, S20 and BY28) and coarser material from these adjacent environments becomes incorporated into the predominantly muddy intertidal sediments. Restronguet Creek, however, shows a clear gradient trend with the highest proportion of fines occurring in sediments taken from the upper sample stations and least occurring in sediments taken from the lower Creek sample stations. The trend shown by the Fowey Estuary is the reverse of this, with the lower reaches being dominated by fine material, possibly the result of spillage from the china clay port and/or the physical affects brought about by the greater depth of water reducing winnowing effects (within wave base fine material is moved up stream by the incoming tide). Using the mean grain size distribution values, the rank order of the proportion of fine material <63μm with respect to the sample locations is:

Restronguet Creek>Fowey>Avon>Erme and this ordering is the same as for the <16μm category.

It is evident that each of the sample locations are classified as estuarine mudflats with the majority of the Restronguet Creek samples forming the upper mudflat sub-group (Pejrup, 1988). The other sample locations are classified as lower mudflat/mixed mudflat (Pejrup, 1988). Despite the variation shown the majority of the samples are dominated by silt sized material.

4.4.4 Mineralogy

Mineralogical analysis of the sediment samples taken from Restronguet Creek (and St Clements in the Carrick Roads) and the baseline/control estuaries show that, in general, the same minerals appear; e.g., quartz, biotite and muscovite mica, detrital clay and lithic clasts of slate (Plates 5 and 6). Of the samples taken the material from St Clements has the largest amount of shell debris and detrital clay (Plate 5, Figures 6 - 8). The occurrence of heavy mineral grains (e.g., apatite, topaz and tourmaline) is rare with respect to the Erme and Avon samples (Plate 6, Figures 1 - 3), but more common in the Fowey samples as are mica flakes (Plate 6, Figures 4 and 5). The granite intrusions of St Austell and Bodmin are the source of these heavy minerals (Bristow and Scott, 1998; Scott *et al.*, 1998). China clay extraction of the kaolinised parts liberates these usually stable minerals (e.g., topaz) which, once removed, are stored in waste piles and mica lagoons. China clay waste has been historically discharged into the estuaries and more recently accidentally. The mica discharge contains primary and secondary biotite mica, muscovite mica and clay minerals, in addition to rarer heavy minerals (Pirrie and Camm, 1999). All samples from each of the estuaries and Restronguet Creek show an enrichment (>40%) in non-mineral debris in the coarser fractions greater than 500µm (Figure 4.13). The Avon and Erme samples contain the highest proportions of this non-mineral debris, approximately 60%. This detrital material (both organic and inorganic) is a mixture of shell fragments, diatom frustules, polychaetes, ostracods, unspecified crustacea, and aquatic and terrestrial plant material (Figure 4.13). Estimations of the sediment samples <500µm and thin section analysis show that the proportions of each mineral varies. Lithic clasts of slate and vein quartz are common in the Fowey, Avon and Erme samples (up to 70% in some examples) but are more rare in the samples taken from Restronguet Creek (Plate 5). Quartz makes up 20 - 30% of the Restronguet Creek samples (with the exception of H23) but is predominant in the Erme and Avon samples (>50%). There are examples of quartz grains showing textural variation and Figure 4.14 shows an example of strained quartz found in the Avon samples. The

Fowey samples (Figure 4.15) are dominated by muscovite mica (>60%) with lesser proportions of biotite mica (approximately 15%).

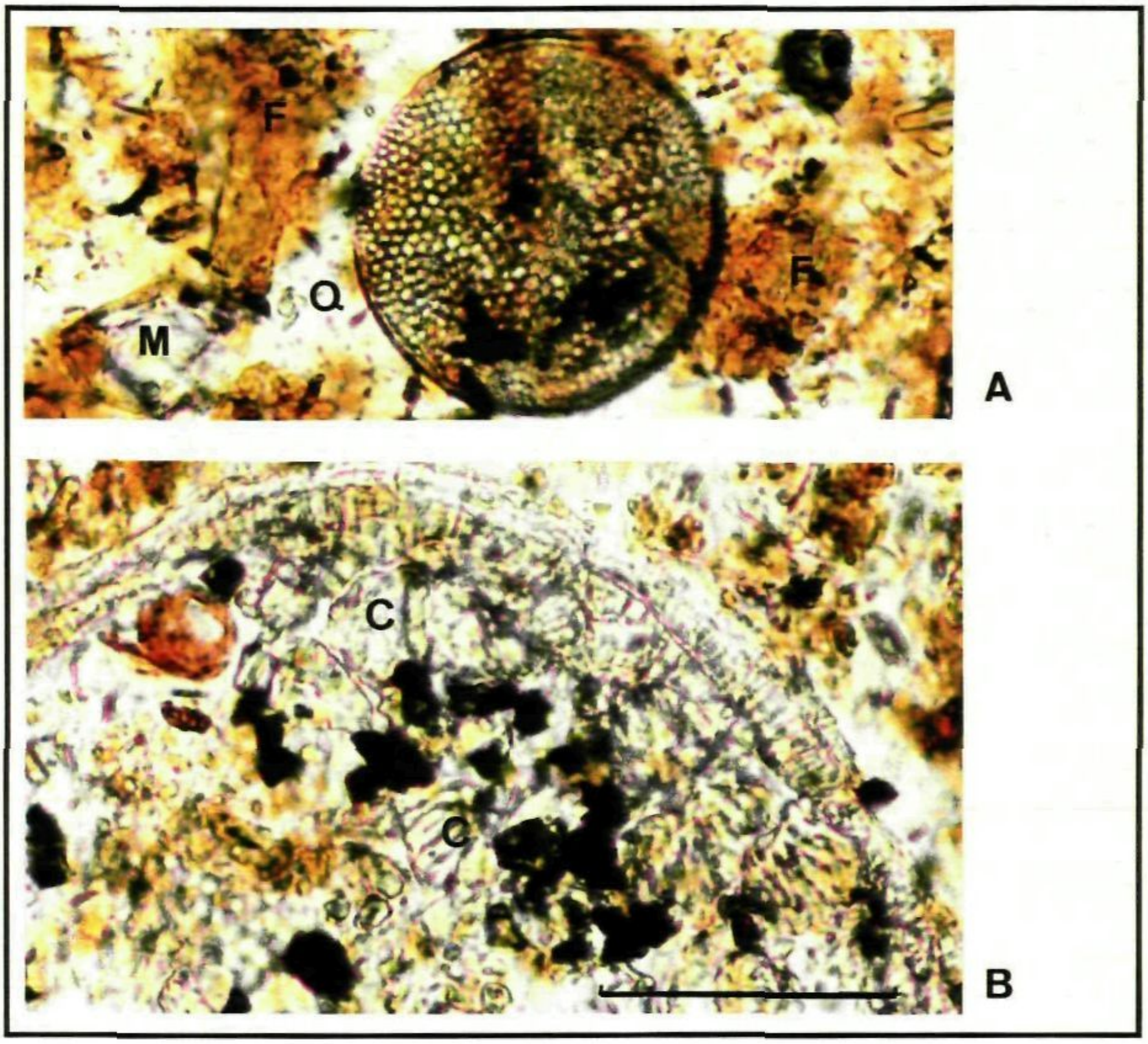


Figure 4.13: Thin section composite colour of sediments from Restronguet Creek. a) diatom frustule and b) bivalve with calcite crystals (C), background comprises Fe aggregated sediment grains (F), musccovite mica (M) and quartz (Q). Scale bar = 54μm.

Muscovite and biotite mica (Figure 4.15) also appear in the Restronguet *Creek (approximately 5%), Erme and Avon samples (8% and 3% in each case). The* Fowey samples are similar to the Erme and Avon estuaries but include large quantities of muscovite mica and detrital clay, with some kaolinite books throughout the size fractions (Plate 6, Figure 4). The relatively fresh kaolinite books probably originated from the china clay extraction area.

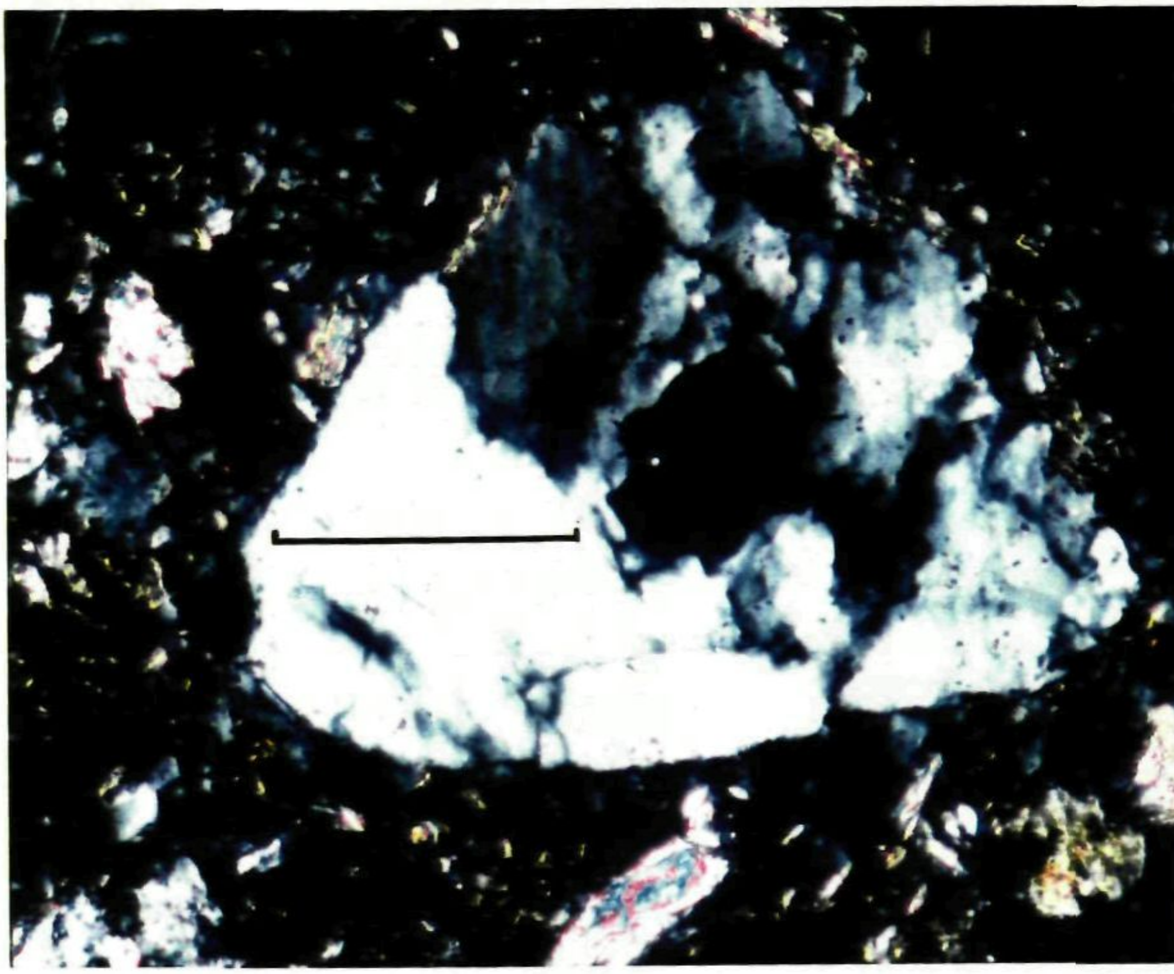


Figure 4.14: Thin section of strained quartz in sediments from the Avon Estuary. In cross polarised light. Scale bar = 110µm.

Heterogeneous aggregates (floccules) consisting of biogenic matter, quartz and detrital clay particles are common in the <63µm fraction from all sample stations but are particularly common in the Restronguet Creek samples (Plate 5, Figures 2 - 5). These iron/clay aggregates comprise a mixture of organic, biogenic (diatoms), detrital clay, pyrite and quartz particles. Scanning electron microscope analysis shows that the individual particles making up the aggregates vary considerably in size and range from 2 to 100µm (Plate 5, Figures 2 and 5). Sample station H23, is the exception to this and has a high proportion (approximately 35%) of Fe-coated quartz mine waste. In plane polarised light (PPL) the high concentration of Fe is evident by the strong orange - brown colour of the sediments, particularly with respect to Restronguet Creek (Figure 4.16). The Fowey samples show less iron relative to Restronguet Creek and the Erme and Avon with negligible amounts. Shell fragments increased in abundance down each estuary.

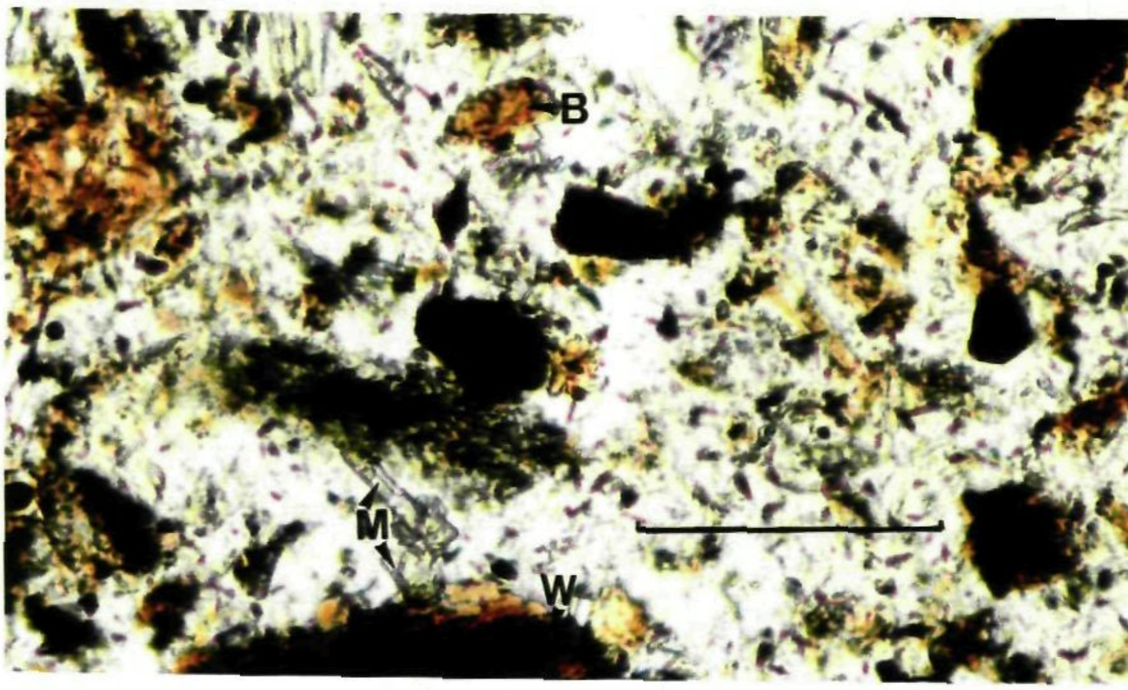


Figure 4.15: Thin section of sediment from the Fowey Estuary. Comprising biotite and muscovite mica flakes (B and M) and wood/leaf material (W). Scale bar = 110μm

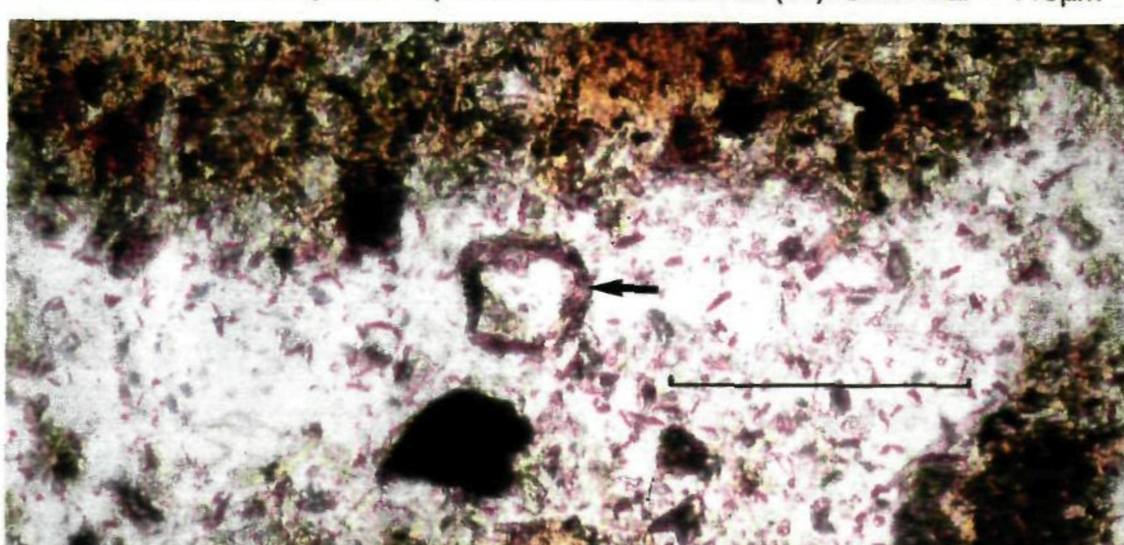


Figure 4.16: Iron coated quartz (arrowed) in sediments from Restronguet Creek. Thin section, scale bar = 110μm.

Plate 5

Sediment grain size and mineralogy: Restronguet Creek

Figure 1. Lower magnification view of sediment from Restronguet Creek, station D1. The individual grains are aggregated together to form heterogeneous floccules (HF).

Figure 2. Enlargement of Figure 1 showing in more detail the composition of the aggregated grains, which include pennate diatom frustules (D).

Figure 3. Enlargment of diatom frustule in Figure 2, individual grains of quartz can be seen amidst detrital clay and mica flakes. Cassiterite (C) and detrital clay/mica flakes (M).

Figure 4. Quartz grain (Q) to which smaller flakes of mica and detrital clay (DC) adhere.

Figure 5. Enlargement of Figure 2, showing a heterogeneous floccule comprising detrital clay (DC), mica flakes (M) and organic debris (O).

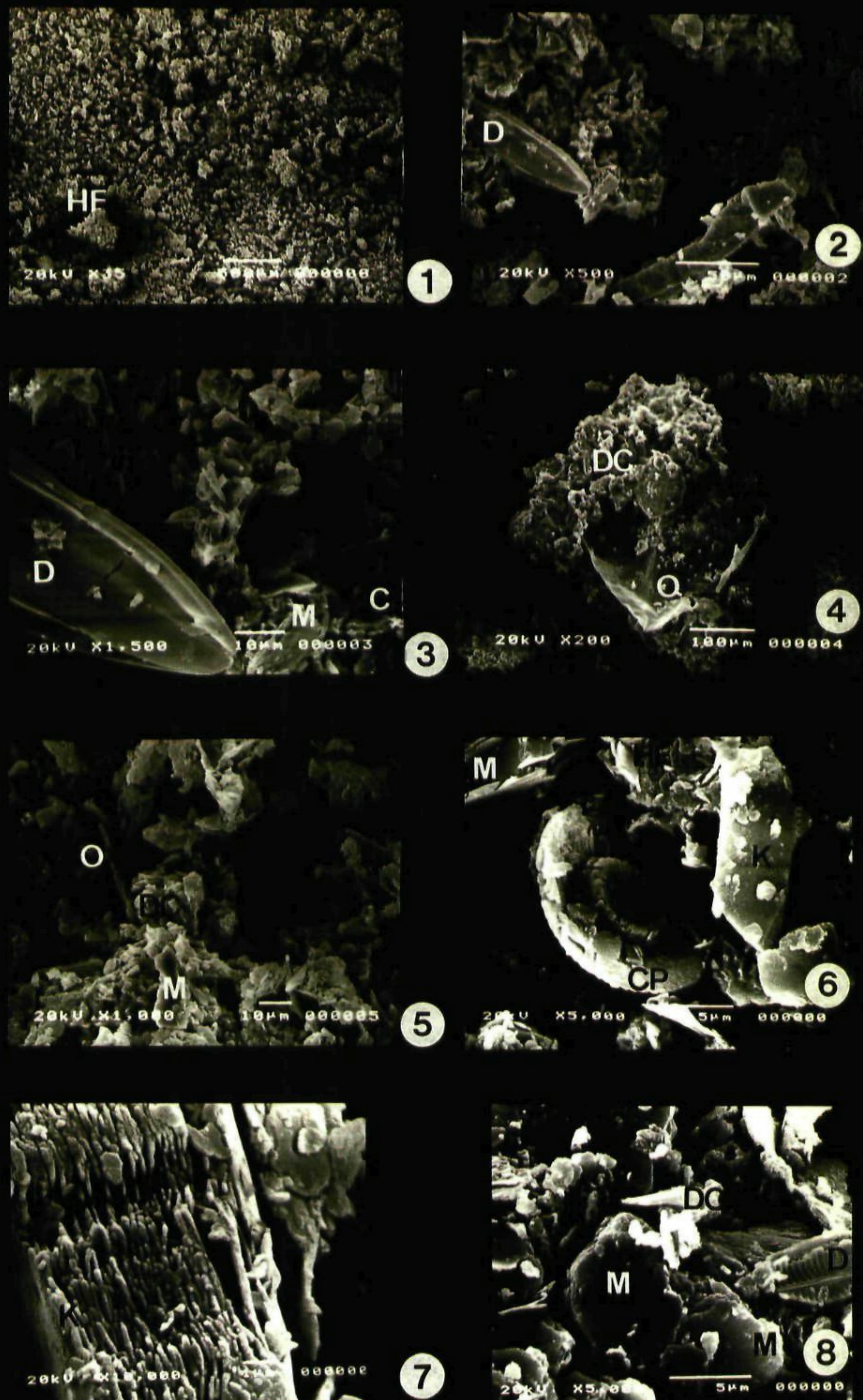
Sediment grain size and mineralogy: St Clements

Figure 6. Sediment comprising shell debris, coccolith plate (Cp), kaolinite (K), mica/detrital clay (M) and heterogeneous floccules (HF).

Figure 7. High magnification view of a kaolinite book (K).

Figure 8. Sediment comprising mica (M), detrital clay (DC) and a diatom (D).

Plate 5



HF
1
D
20kV X500
2
D
M
C
20kV X1,500
10μm 000003
3
DC
O
20kV X200
100μm 000004
4
O
M
10μm 000005
5
M
K
CP
X5,000
5μm
6
K
7
DC
D
M
M
5μm 000000
8

Plate 6

Sediment grain size and mineralogy: Control estuaries

Figure 1. Sediment sample from the Erme Estuary, station HP4, autumn 1993 showing aggregated grains of heterogeneous floccules (HF) of detrital clay and mica flakes (M), and quartz (Q).

Figure 2. Sediment sample from the Avon Estuary, station A1, summer 1995, showing individual lithic clasts (L), quartz, organic debris (O), shell fragments (SF) and aggregated grains of heterogeneous floccules (HF) of detrital clay and mica flakes.

Figure 3. Enlargement of Figure 2.

Figure 4. Sediment sample from the Fowey Estuary, station StW1, summer 1994, comprising individual grains of quartz, lithic clasts, shell fragments and mica flakes. In addition, there are large floccules of detrital clay and mica flakes (M).

Figure 5. Enlargement of Figure 4 showing the heterogeneous floccules of detrital clay and mica flakes (M). Pennate diatoms (D) and a *Reophax moniliformis*, R, are also present.

Plate 6

M
Q
HF
15kU X500
50µm 11111
1
L
O
L
HF
SH
X150
100µm
2
HF
X350
3
M
5kU X1,500
10µm
4
M
R
D
15kU X750
10µm 11111
5

4.5 Water quality

i) Metals

There were large variations in the metal concentrations in water recorded at the Devoran monitoring station. The raw data (Devoran monitoring station) for each metal have been calculated to find the monthly mean (Figure 4.17). While the Wheal Jane mine was inoperative, but before the minor discharges began in the autumn of 1991, the water was of relatively good quality with low concentrations of all the metals analysed (Table 4.3). At the time of the discharge all metal concentrations in the Carnon River at the point of discharge, increased to levels above that previously recorded (Environment Agency). Each of the metals follows a trend with coincidental peaks and troughs (Figure 4.17).

Element	Previously Recorded	At time of Discharge
Al	no data	11.5 ppm
Cu	<0.5 ppm	2 ppm
Pb	0.01 ppm	0.1 ppm
Fe	<5 ppm	160 ppm
Zn	<9 ppm	130 ppm
Cd	<10 ppb	190 ppb

Table 4.3: Monthly means of metals in solution. Recorded at Devoran monitoring station before the main discharge and at discharge.

Throughout the period of water analysis that is included here (1991 - 1996) the levels of metals have been erratic with sharp peaks reflecting the variable nature of the problem caused by fluctuating rainfall and recharge, particularly in the winter months. Cadmium is the exception and has produced a relatively stable profile with fewer large peaks.

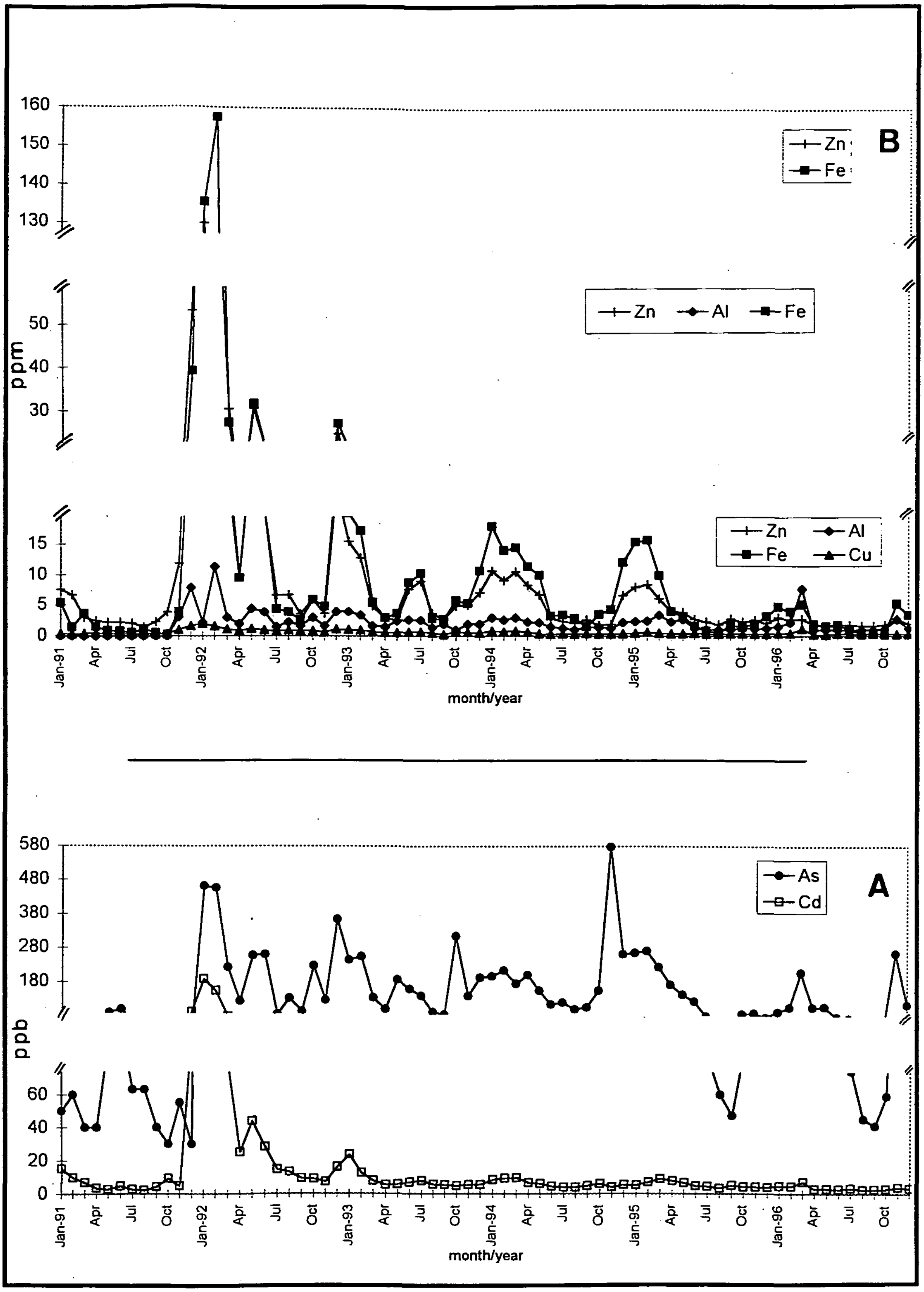


Figure 4.17: Monthly mean metal concentrations recorded at Devoran monitoring station between 1991 and 1996. a) Cd and As concentrations in ppb, and b) Fe, Al, Zn and Cu concentrations in ppm.

Metal concentrations did not return to the pre-discharge levels for three years and this was due, in some part, to the small episodic discharges which have occurred since the main discharge and, particularly during the winter. The winter levels of most metals rise relative to the summer as during the winter one or more of the following may occur:

- Discharge of untreated mine drainage from Mt. Wellington, County, Wheal Jane and Nangiles Adits (Figure 1.8).
- Direct seepage through the river bed (Section 1.5.1).
- Stronger river currents scour ochre from bank vegetation and channel gravel.
- High water flows emanating from the other abandoned mines (Figure 1.7).

It was thought that dilution and dispersal effects, which would be greater in the winter, would reduce the concentration of metals relative to the summer, but the converse has occurred, the probable cause being the changing water levels in the mine workings (Chapter One). During periods of high rainfall, some of the mine water is diverted from Jane adit to the upper Nangiles adit to reduce pressure on the primary treatment system (C.Fileman, Environment Agency, pers.comm., 1995). Between 1992 - 1994 untreated water was discharged each day from Nangiles Adit varying from 55 to 600 $x10^6$ litres on each occasion (Camon Update, Environment Agency, 1992 - 1994).

The values obtained at the 'fixed' station showed tidal incursion had effectively been diluting the metal enriched channel water. The dilution factors varied for each metal, but in general the concentrations changed from ppm to ppb with the exception of Cd and As but which were reduced by one or two orders of magnitude (Table 4.4).

Metal	Devoran Station	Fixed Station
As	115 - 365ppb	5.5 - 5.7ppb
Cd	8 - 26ppb	0.65 - 1.39ppb
Ni	0.1 - 0.2ppm	0.1 - 20.9ppb
Fe	4.7 - 35.5ppm	3 - 449ppb
Pb	0.01 - 0.03ppm	0.22 - 0.88ppb
Cu	0.55- 1.5ppm	13 - 33ppb
Zn	6 - 26ppm	446 - 1540ppb

Table 4.4: Metal concentrations recorded at the monitoring stations at Devoran and the "fixed station". Data for the month of January, 1993. All values change from parts per million (ppm) to parts per billion (ppb) with the exception of Cd and As.

***ii)* Acidity**

The pH levels recorded also indicated poor water quality. In the period January 1991 to October 1991, before the small discharges began, the mean pH of the water entering the Creek was in a range of 5.8 to 6.5 (Figure 4.18). At the time of the main discharge, in January 1992, pH values (river water) ranged between 3.2 and 3.75. Levels continued to fluctuate between pH 3.5 and 5.5 (river water) from February 1992 to June 1994. From the summer of 1994 pH has remained above 5.4. As the data for 1995 (April onwards) and 1996 show, pH (mean) has consistently remained above 6.0. The rates of rainfall, recharge and general groundwater quality emanating from the Wheal Jane and other abandoned mines, account for the variability shown between seasons and years, and is not a direct function of the amount of liming which has been determined to match flow rates from Wheal Jane mine only (Catherine Fileman, Environment Agency, pers.comm., 1993). Within the area above TC8 and H23 pH values remained below 6.4 from 1992 to 1994 and the highest values for this period were recorded at PI30 at pH 6.8 - 7.0. The level of acidity has now stabilised and although a gradient is still present, with the lowest values ocurring at D1 and the highest at station PI30, the pH of the water is approaching that of the control estuaries which are commonly between pH 7 and 8.5.

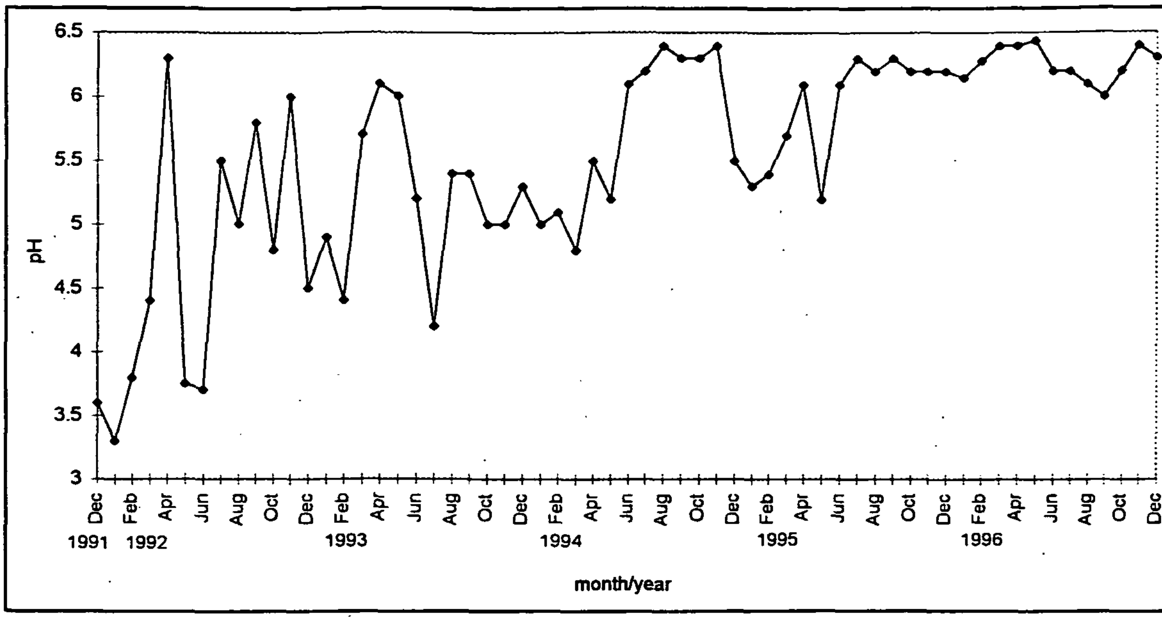


Figure 4.18: Monthly mean pH data recorded at Devoran monitoring station between 1991 and 1996.

The pH of the pore water also shows an increase with time and at stations D1 and C19 values increased from 3.2 in June 1992 to 6.9 in July 1996. The lower Creek stations CY16, TW27, BY28 and PI30 had pH values which varied between 6.8 and 7.4 for the same period. The other Creek stations; TC6, TC8, TC9, P10, PC13 and H23 varied between 6.4 and 7.1. The pH of the pore water in the control estuaries has generally been above 8.0 with the exception of the Fowey Estuary which is slightly acidic throughout and varies between 6.7 and 7.5.

The rise and continued stability of river and pore water pH is an important development as under neutral pH sediment bound metals cannot be leached (Stubbles *et al.*, 1996a).

4.6 Organic carbon, nitrogen and the C/N ratio in the sediments

i) Restronguet Creek

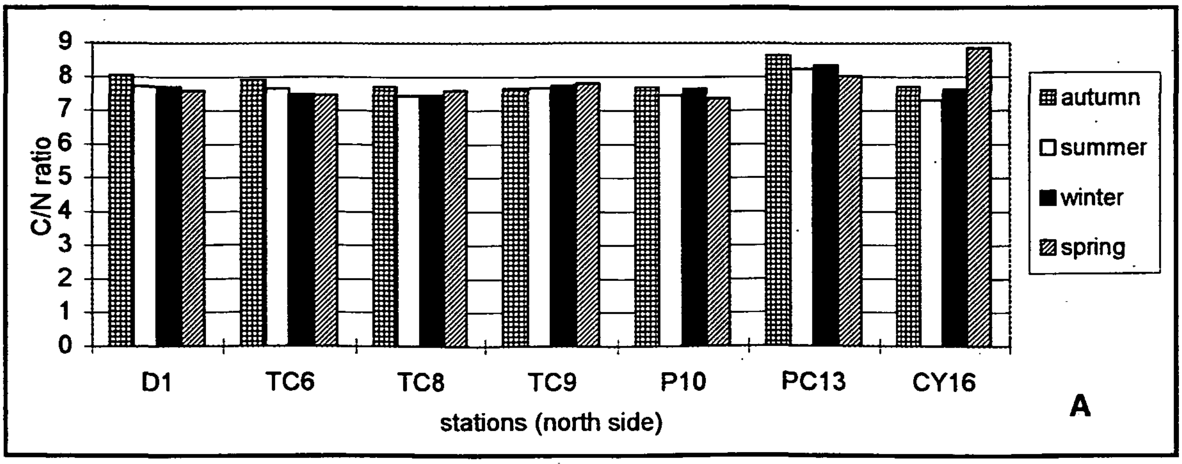
The carbon values obtained for Restronguet Creek range between 1.37% and 3.89%, with between 0.21% and 0.49% nitrogen. The C/N ratio ranged between 6.4 and 10.3. The range for each parameter was moderately narrow and indicated no significant variation on the north side of the Creek between each station, season or year. The south side of the Creek did show greater variation.

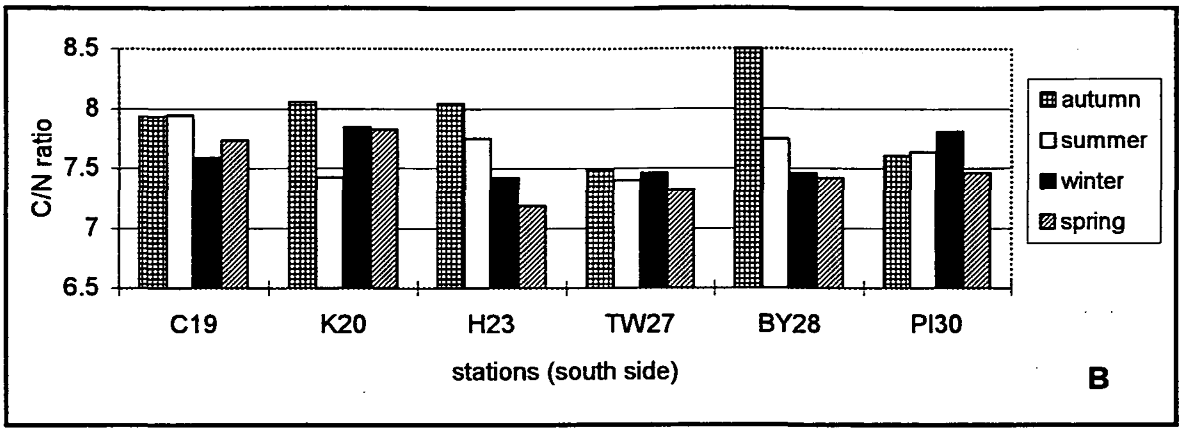
For simplicity, the carbon, nitrogen and C/N ratio have been averaged for each season. Seasonal mean values of carbon and nitrogen in Restronguet Creek varied, therefore, between 1.57% and 3.68%, and 0.27% and 0.42% respectively but in general the values were greater than 2.5% for carbon and 0.34% nitrogen (Table 4.5).

Location	% Carbon	% Nitrogen	C/N ratio
R. Creek	2.69	0.34	7.8
Erme	3.7	0.42	8.6
Fowey	3.46	0.36	9.51
Avon	2.44	0.31	8.03

Table 4.5: Mean organic carbon, nitrogen and the C/N ratio

The mean C/N ratio varied between 7.03 and 9.10 (Figure 4.19, a and b) but in general values were below 8. Station H23 and to a lesser extent, BY28 showed an incremental decrease between each of the seasons with autumn the highest and spring the lowest. The data for Restronguet Creek show, therefore, that the available nutritional content of the sediments is high.

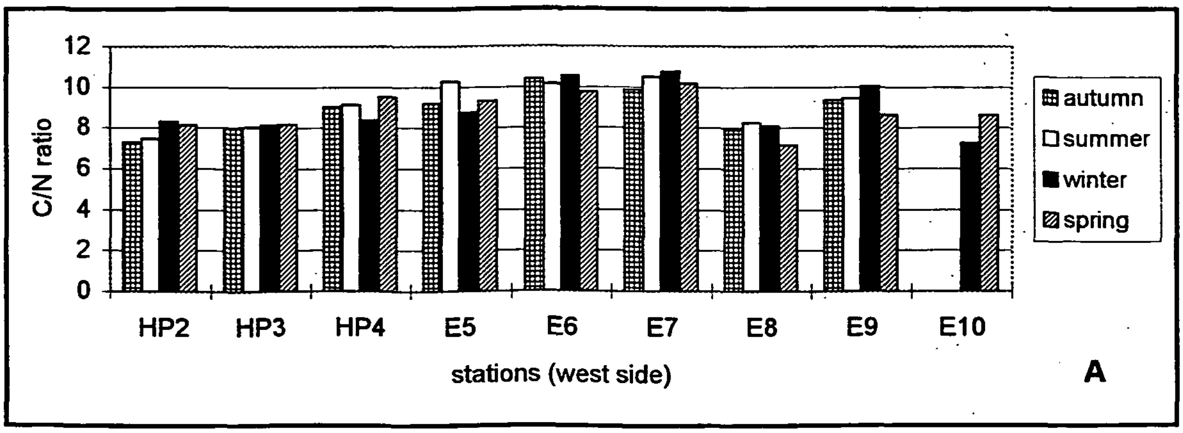


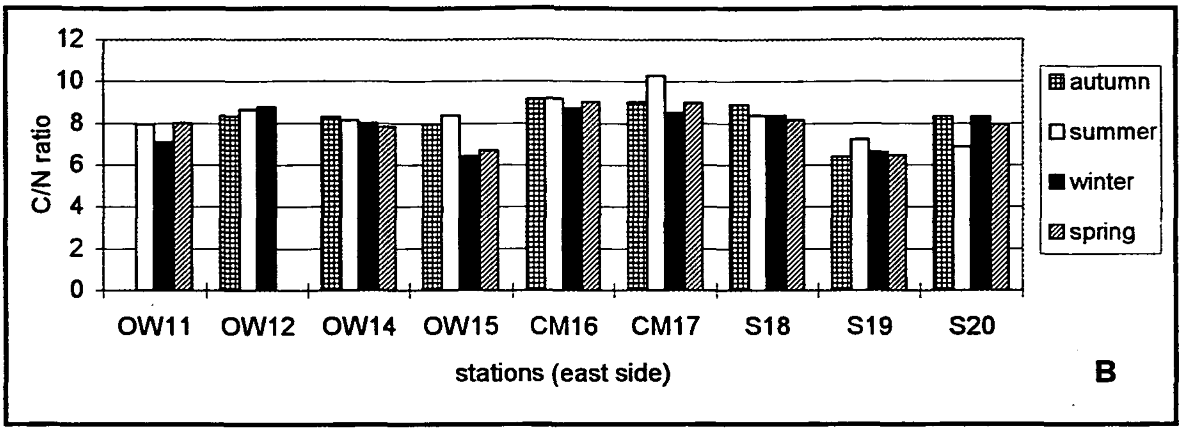


Figures 4.19: Seasonal variation in the C/N ratio, Restronguet Creek. a) north and, b) south side.

***ii)* The Erme Estuary**

The variation in carbon and nitrogen in the Erme sediment samples is high, with carbon varying between 1.77% and 6.43%, and between 0.22% and 0.79% of nitrogen. The C/N ratio varied between 6.40 and 10.77 with the distribution being random between stations and seasons (Figure 4.20, a and b). Overall, stations E6, E7, CM16 and CM17 had the highest ratios and for the same period the C/N ratio was comparable to the mean range for Restronguet Creek.

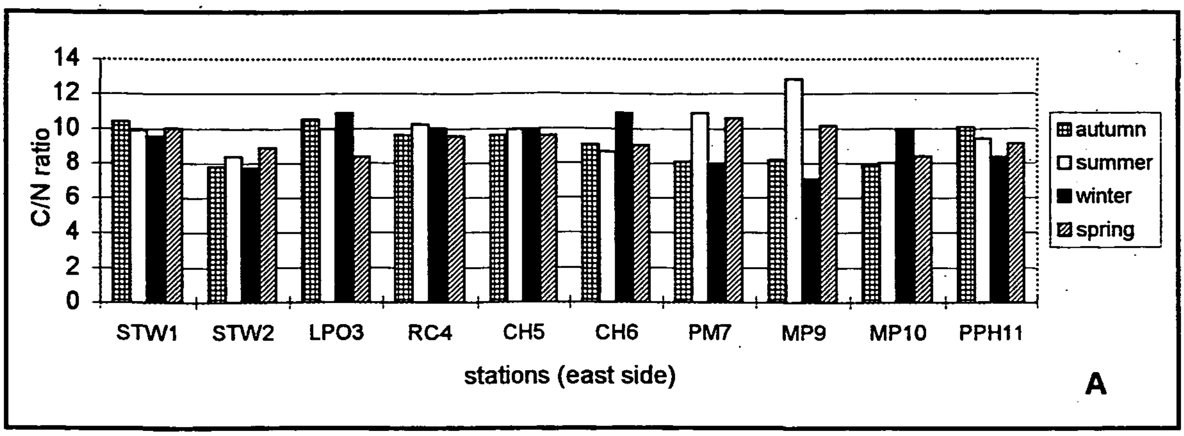


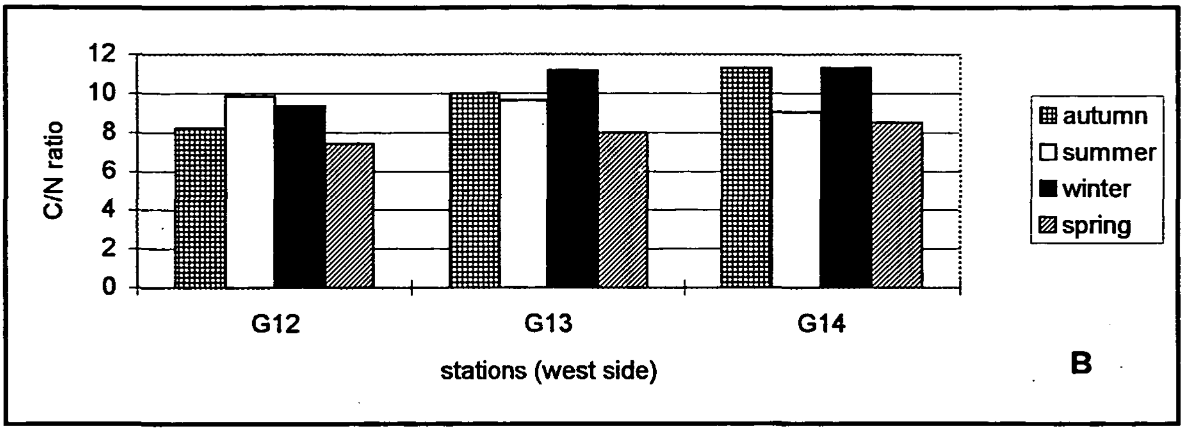


Figures 4.20: Seasonal variation in the C/N, Erme Estuary. a) west side and b) east side.

iii) The Fowey Estuary

The Fowey Estuary samples showed high variance between stations, particularly in the winter and varied between 1.8% and 7.7% carbon, and 0.18% and 0.71% nitrogen. The C/N ratio varied between 7.1 and 12.9 (Figure 4.21, a and b) and compared to the same period had values that were dissimilar to Restronguet Creek with the maximum values being greater in the Fowey Estuary. Stations StW1, RC4 and CH5 showed the least variation between seasons and stations LPO3, PM7, MP9 and G14 showed the most. Overall, the majority of values were below 10, and on the west side of the estuary the spring ratio was the lowest, as for Restronguet Creek (Section 4.6, *i*).

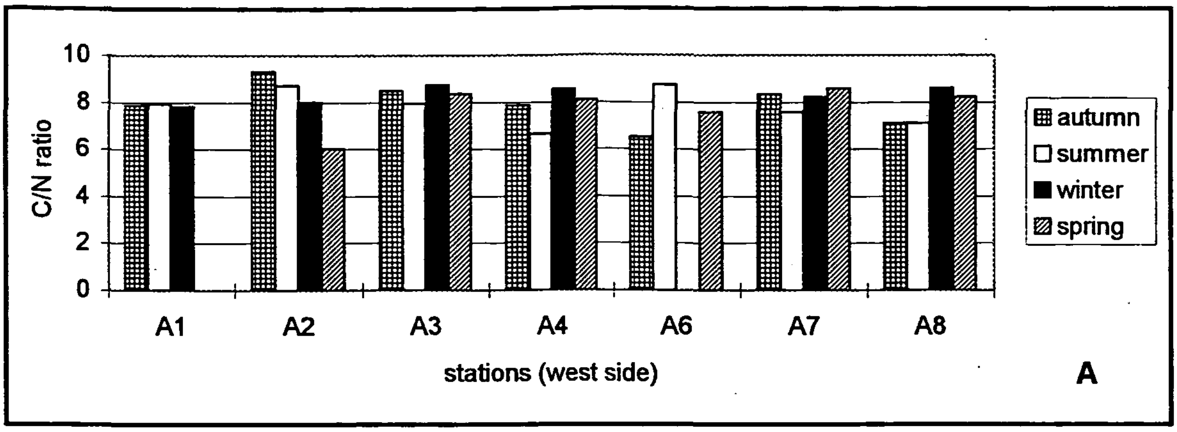




Figures 4.21: Seasonal variation in the C/N ratio, Fowey Estuary. a) east side and b) west side.

iv) Avon Estuary

The Avon samples varied between 1.36% and 4.01% carbon, and, 0.17% and 0.7% nitrogen which are the lowest values for the control estuaries. The majority of C/N ratios were comparable to Restronguet Creek for the same period and varied between 6.03 and 11.96 (Table 4.5). Station A2 showed an incremental decrease between the seasons with the autumn being higher than spring (Figure 4.22, a and b) and partial incremental seasonal distribution was shown by stations A10, A11 and A12 (Figure 4.22, a and b).



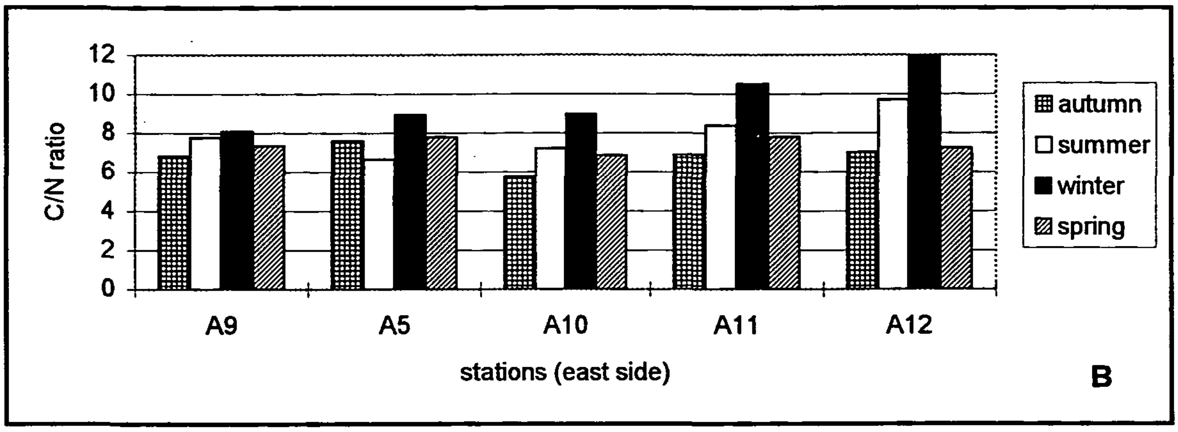


Figure 4.22: Seasonal variation in the C/N ratio, Avon Estuary. a) west side and b) east side.

In summary, each location had C/N ratios which fall below the value proposed by (De Rijk, 1995) of 25 and the lower value of 17 by Ristola *et al.,* (1999) which are considered to be adequite for most organisms. The C/N ratio is an important indicator of available nutrition for the foraminifera and particularly for the agglutinating species with a preferred detrital feeding habit. A low C/N value of below 25 indicates greater organic carbon decomposition and hence adequite diet for the foraminifera.This suggests that nutrition is not a factor which would explain the absence of the agglutinated species in Restronguet Creek (Chapter Five, Section 5.7.2).

4.7 Sediment geochemical analysis

4.7.1 Introduction - Sediment and crustal background levels

The background levels of trace elements in soil and rock vary with region (Rose *et al.*, 1979) but the elements Ca, Al and Fe always produce the highest concentration range in soils as global means (Rose *et al.*, 1979). The type of soil is an important factor as sediments with high concentrations of Fe-oxide also contain higher concentrations of most elements relative to Mn-oxide sediments. Both these elements have high adsorption capacity for most other elements (Rose *et al.*, 1979). The exception to this is Cu which is highest in both types of soil, and also for soils with high goethite (amorphous Al-oxide) and humic contents because of the greater adsorption affinity shown by the Cu^{2+} cation. In general terms, the order of concentration in medium soils are as shown in Table 4.6.

As with soils, elemental concentrations in crustal rocks vary with rock type. Limestones, for example, usually have low abundances of heavy metals and shales generally have the highest. The range of crustal concentrations of selected metals in sedimentary rocks is shown by Table 4.6.

	Al	Fe	Zn	Pb	Ni	Cu	As	Cd
Crustal	11800	3800-47000	21-100	5-25	2-68	5-42	1.1-12	0-0.3
Soils - medium	37000	21000	36	17	17	15	7.5	0.1-0.5

Table 4.6: Mean range of each element (ppm) in crustal rocks and medium soils. (UK mean range from Rose *et al.*, 1979).

The order of concentration in crustal rocks is therefore: Al>Fe>Zn> Ni>Cu> Pb>As>Cd. This is similar to that found in soils apart from Cu which shows relative depletion in soils, and Cd and Al which show enrichment in soils relative to sedimentary rocks. Aluminium and Fe show very high concentrations in both soils and crustal rocks and this may be due to the enrichment of Al and Fe within the lithosphere and their moderate mobility (Rose *et al.*, 1979). Average sedimentary crustal concentrations of the true heavy metals show nickel to be the highest at 30 ppm compared with 19 ppm for Cu and 13 ppm for Pb.

4.7.2 Sediment geochemical temporal variation - Restronguet Creek

The autumn data sets show that there has been an erratic rather than a progressive decrease in metal concentration each year since 1992 (Appendix 1.1b,c). The data from autumn 1994 onwards show the concentration of the metals Al, Fe and Zn are, in general, greater than for the preceding years, 1992 and 1993. The metals As and to a lesser extent Cu, Pb and Ni show a more varied temporal distribution and occasionally are higher in 1992 and 1993 relative to the other years at certain stations; e.g., station P10, 1993. Comparison of the metal concentrations from samples taken in 1992 and 1996 shows that the metals Fe, Pb, Ni and As have higher maximum values in 1996 relative to 1992. This increase in metal concentrations could be the result of a number of processes:

- The introduction of contaminated particles by the periodic discharges from Wheal Jane mine.
- The continued rise in water pH may result in more metals settling out of solution.

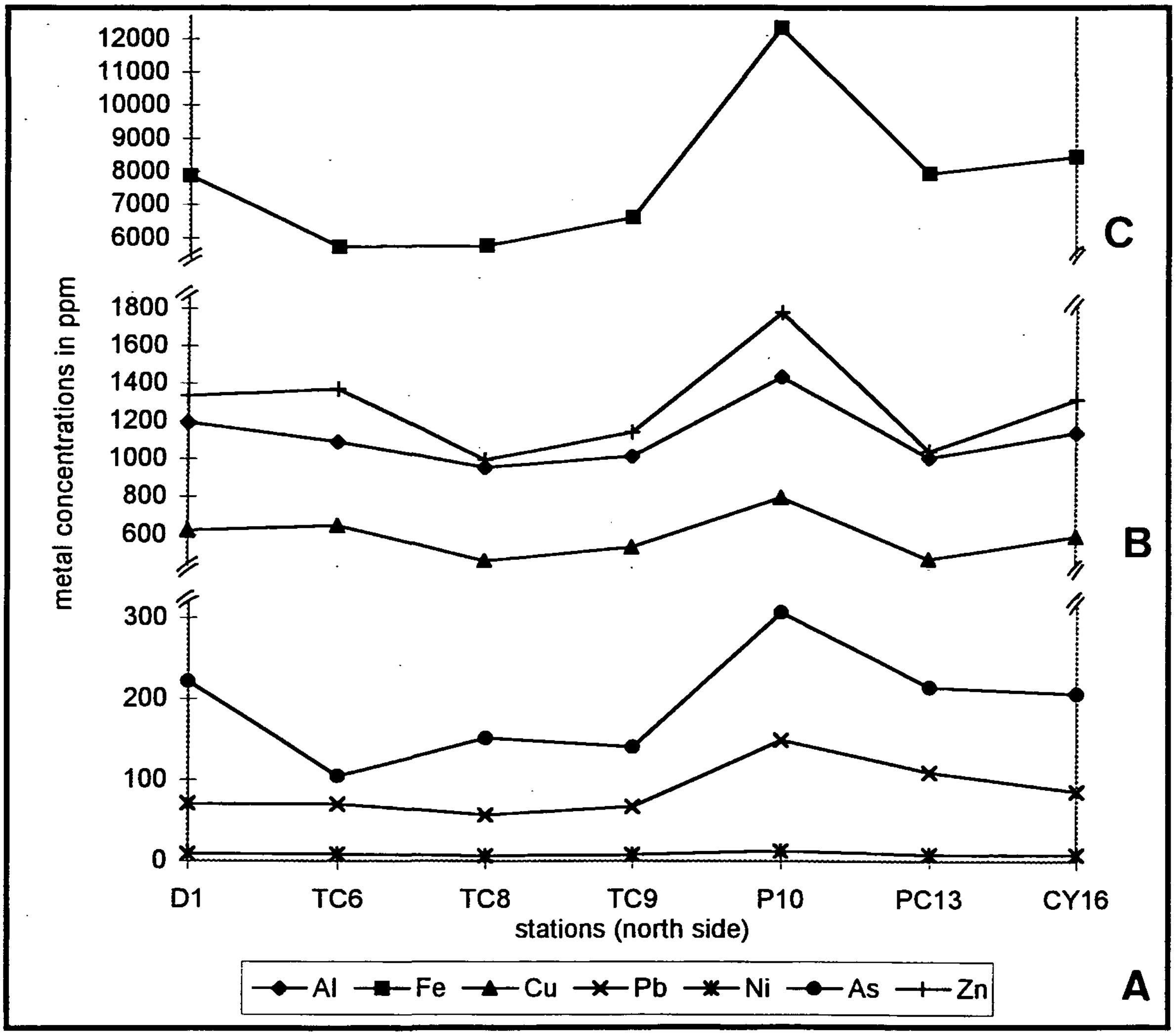
- An increase in polychaete populations, and hence bioturbation, causing mixing of historically more contaminated sediment with more recent, less contaminated material (Bubb and Lester, 1994; Del Valls *et al.*, 1997).
- The return of the wading birds whose feeding activities may cause sediment mixing.
- Boat hauling which vertically and horizontally re-distributes sediment at a localised level.
- Re-colonisation of the macrophytes which modify acidity, metal availability and toxicity (Crowder, 1991).

4.7.3 Spatial variation

i) Restronguet Creek

For spatial analysis the sediment geochemical data (Appendix 1.1c) have been averaged and Figures 4.23, a - c (north side) and 4.24, a - c (south side) show the distribution of each element. With the exception of Zn the range for all other metals is closely similar for both sides of the Creek. It is evident from these diagrams that neither side of the Creek shows a recognisable trend in metal concentration down the Creek. Figure 4.24a, however, does show that the element Cu is higher at stations C19 and K20 relative to PI30 on the south side. The sharp decrease in each metal at station H23 (Figure 4.24, a - c) relative to the other sample stations is significant and may reflect the different sediment grain size distribution and mineral composition there, having less silt sized material and a higher quartz composition (Sections 4.4.2,*i* and 4.4.5).

On the north side metals Pb and As show a more erratic distribution (Figure 4.24a) which may reflect reworking of past air borne impacts (historical) of these metals, particularly Pb, from the smelter that once occupied a site at Penpoll Creek. Spillage of As in transport may account for the erratic distribution of As. Restronguet Creek was the only route available for the transportation of purified As from Bissoe (Chapter One, Section 1.5.1, *i*) and it has been recorded that numerous vessels were grounded and damaged in the Creek during the working period of Bissoe (Simpson, per. comm., 1993).



Figures 4.23: Line graphs of the distribution of sediment-bound metals in Restronguet Creek (north side). a) As, Ni and Pb, b) Cu, Al and Zn, and, c) Fe.

The north side of the Creek shows no concentration gradient and station D1 is occasionally only slightly above that for each element relative to CY16. All the metals, but particularly Pb, are markedly higher at station P10 and to a lesser extent at PC13 and CY16 (Figure 4.23, a - c) and this suggests that there is an additional source of metals here which reflects proximity to the previously mentioned old lead smelter which was demolished in the 1930's (Chapter One, Section 1.5.1).

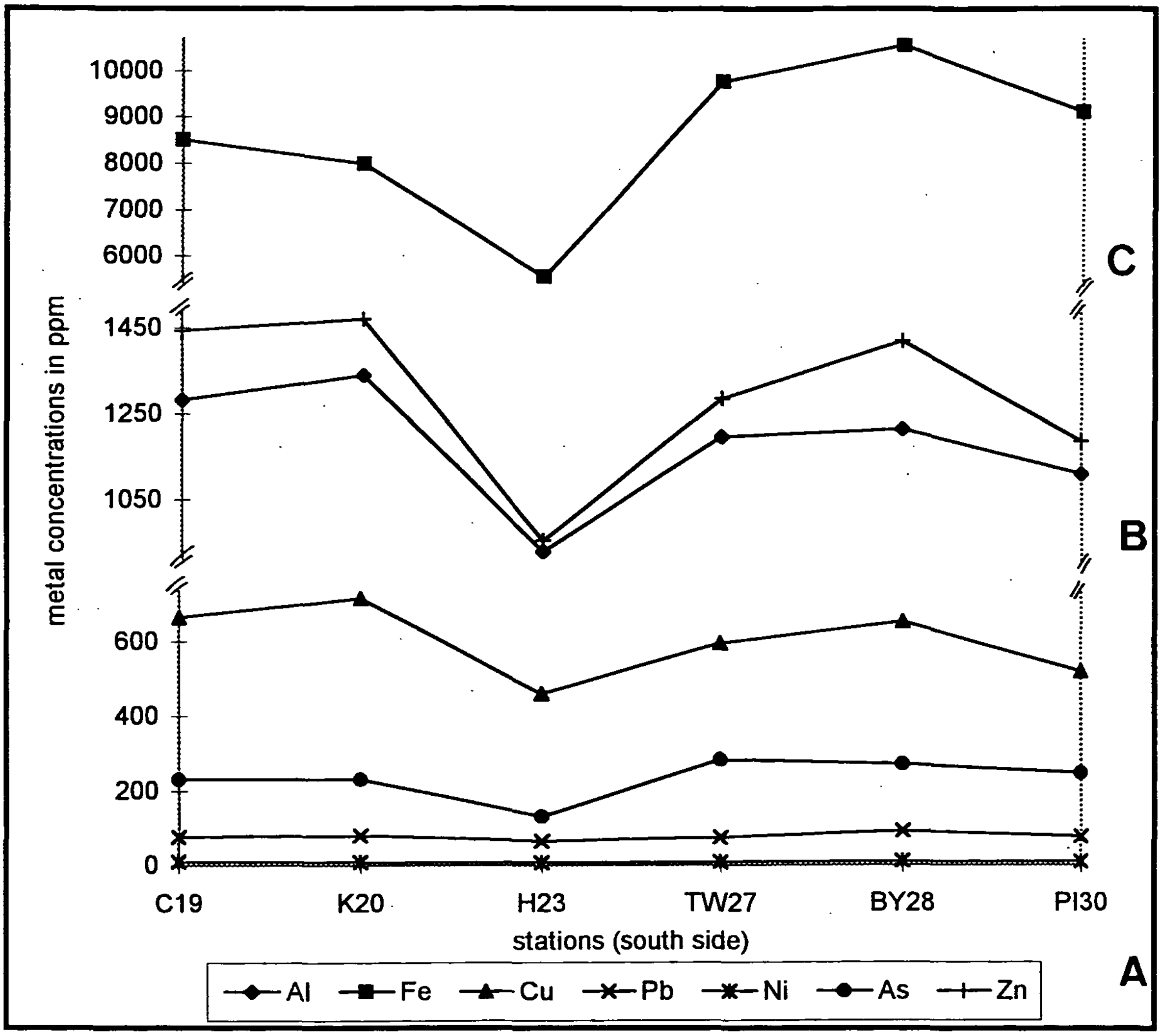


Figure 4.24: Line graphs of the distribution of sediment-bound metals in Restronguet Creek (south side). a) As, Ni and Pb, b) Cu, Al and Zn, and, c) Fe.

***ii*) The Erme Estuary**

The control estuaries also do not show a gradient in metal concentration and, as with Restronguet Creek, the spatial profile is erratic. With respect to the Erme (Appendix 1.2, Figures 4.25, a - d and 4.26, a - c), Zn, and to a lesser extent, Al and Fe, show the most variation between sample stations by an order of magnitude on the west side (Figure 4.25, a - c). On the east side Fe shows the widest range. The creek station CM16 generally had the highest metal concentrations of Al, Fe, Cu, Ni, Pb and Zn. The creek stations CM17 and S18 also have high concentrations of Cu relative to the other stations. On the west side, station E6 has the highest concentrations of the metals Al, Fe, Cu and Pb (Figure 4.26, a - c). The lowest concentrations of the metals Al, Cu, Ni, Zn and Pb are found at the saltmarsh station OW12 (Figure 4.26, a - c).

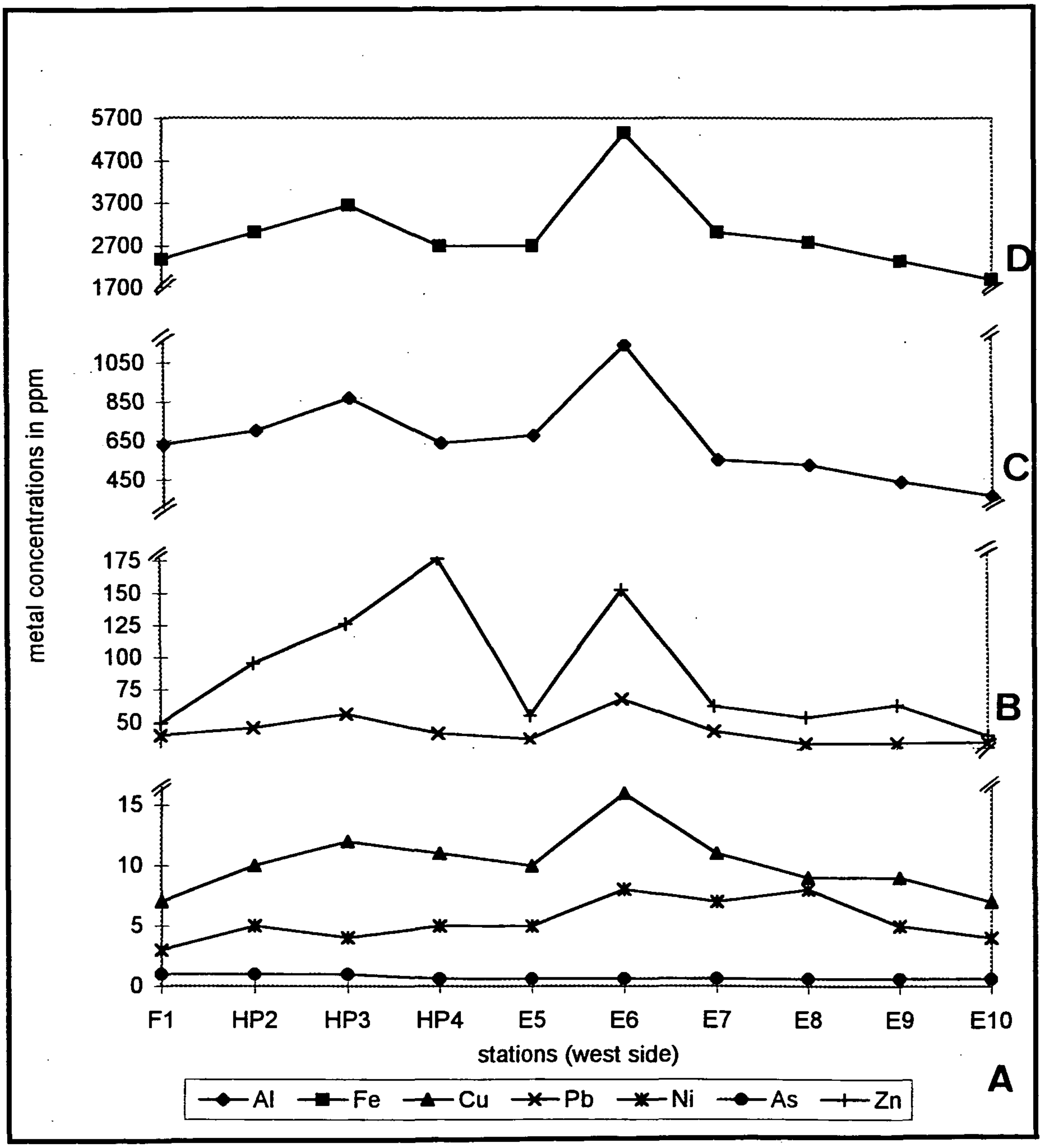


Figure 4.25: Line graphs of the distribution of sediment-bound metals in the Erme Estuary (west side). a) As, Ni and Cu, b) Pb and Zn, c) Al, and, d) Fe.

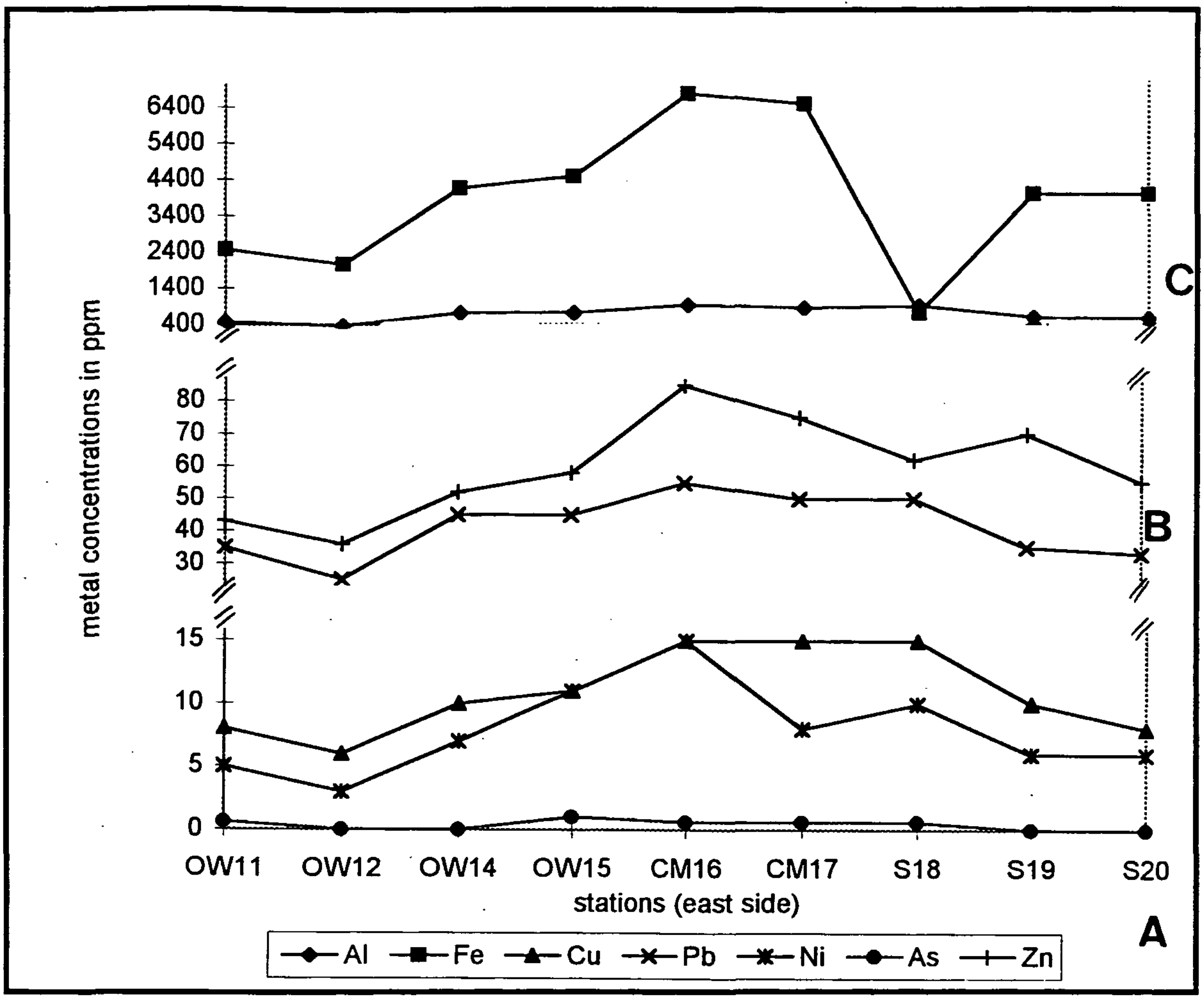


Figure 4.26: Line graphs of the distribution of sediment-bound metals in the Erme Estuary (east side). a) As, Ni and Cu, b) Pb and Zn, c) Al and Fe.

iii) The Fowey Estuary

The Fowey Estuary (Appendix 1.3, Figures 4.27, a and b, and, 4.28, a and b) shows an order of magnitude variation with respect to the metals Al, Pb and Zn, particularly on the east side. The west side of the estuary showed no increase down the estuary with respect to Al, Fe, Cu, Zn and Pb, and station G13 has the highest concentration of these metals (Figure 4.27, a and b). The concentration of nickel remains relatively stable. On the east side of the estuary, station PM7 has the highest concentrations of the metals Al, Fe, Cu, Ni, Zn and Pb (Figure 4.27, a and b). Sample station G12 consistently provides the lowest concentrations of the metals Al, Fe, Cu and Zn (Figure 4.28, a and b).

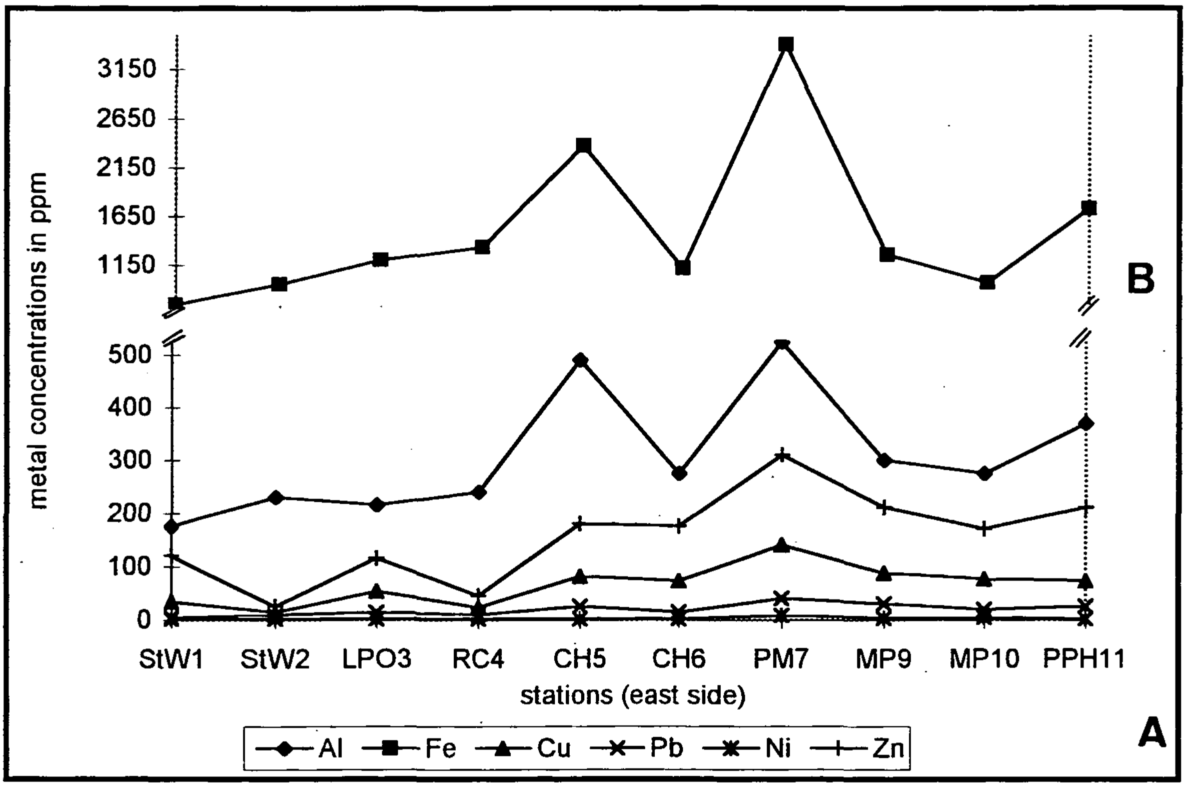


Figure 4.27: Line graphs of the distribution of sediment-bound metals in the Fowey Estuary (west side). a) Ni, Pb, Cu, Zn and Al, and, b) Fe.

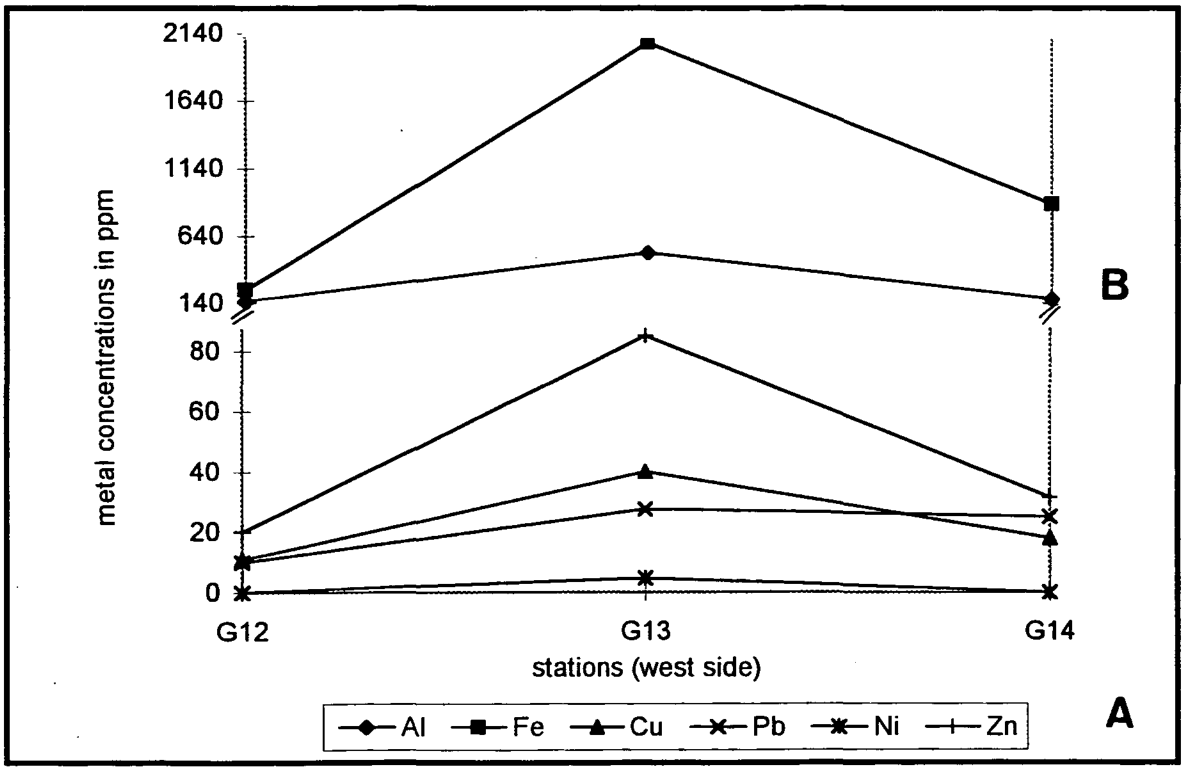


Figure 4.28: Line graphs of the distribution of sediment-bound metals in the Fowey Estuary (west side). a) Ni, Pb, Cu and Zn, and, b) Al and Fe.

iv) The Avon Estuary

The Avon (Appendix 1.4, Figures 4.29, a and b; 4.30, a and b) showed the greatest variation between sample stations with respect to Fe and to a lesser extent Cu and Zn, particularly on the west side. The Avon sample station A7 had the highest concentrations of Al, Cu and Zn (Figure 4.29, a and b). Stations A4 and A1 (with the exception of Fe and Pb) had the lowest concentrations of each metal.

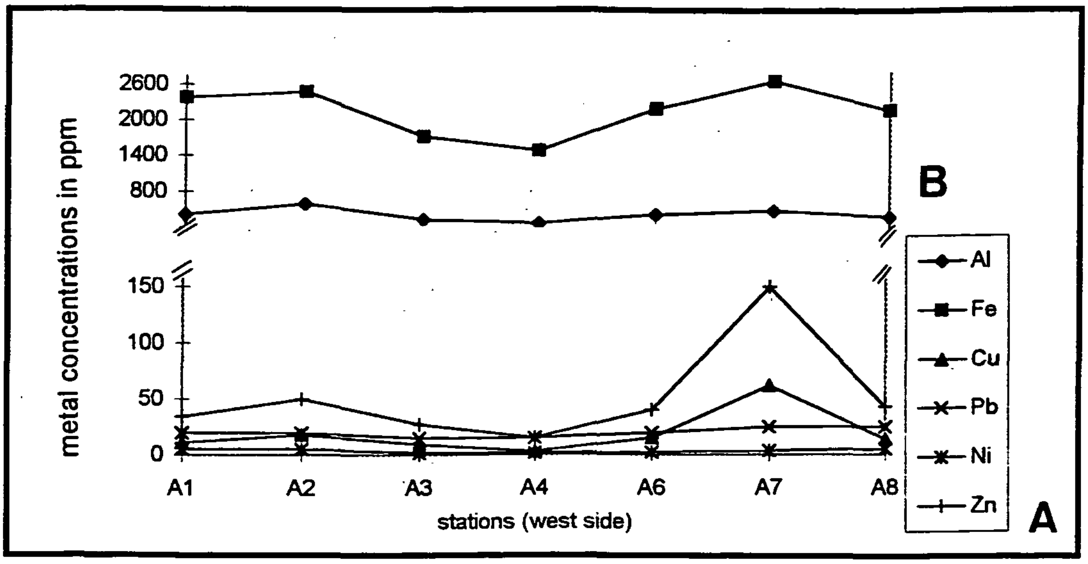


Figure 4.29: Line graphs of the distribution of sediment-bound metals in the Avon Estuary (west side). a) Ni, Pb, Cu and Zn, and, b) Al and Fe.

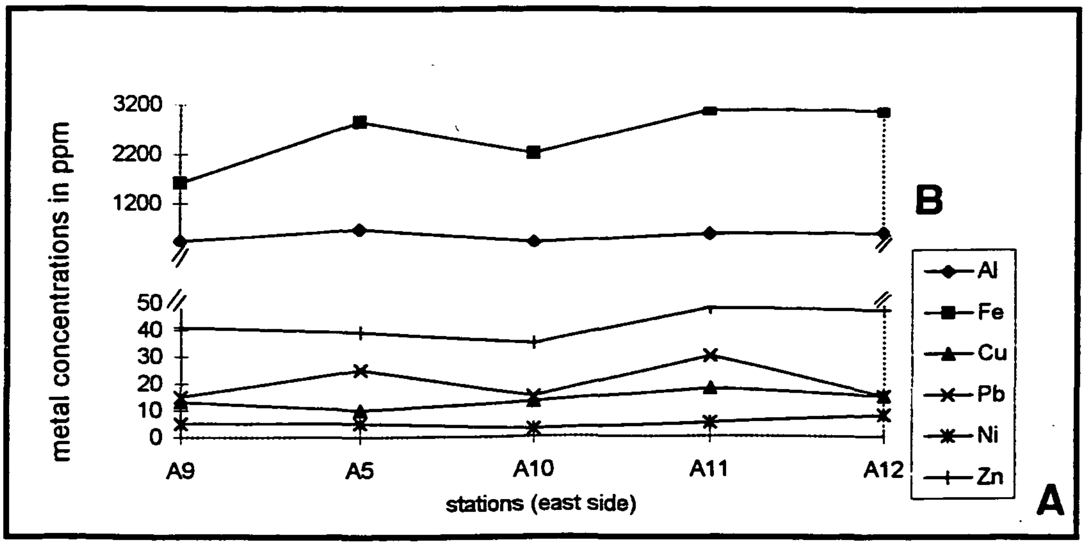


Figure 4.30: Line graphs of the distribution of sediment-bound metals in the Avon Estuary (east side). a) Ni, Cu Pb and Zn, and, b) Al and Fe.

4.7.4 Elemental variation between the sample locations

The similarity and conversely the dissimilarity between Restronguet Creek and each of the control estuaries is graphically shown by the three multi-dimensional scaling (MDS) plots (Figures 4.31 - 4.33). Each plot shows a distinct spatial separation between the Creek and the respective control estuary data. Spatial separation is greatest between Restronguet Creek and the Avon Estuary (Figure 4.33) and the least between the Fowey and Restronguet Creek (Figure 4.32). In each plot the Restronguet Creek points are closely grouped but are not for the control estuary points which are more widely dispersed, indicating greater variation between the samples (Figures 4.31 - 4.33). It is evident, therefore, that the sediment metal concentration distribution observed for Restronguet Creek is distinct to each of the control estuaries.

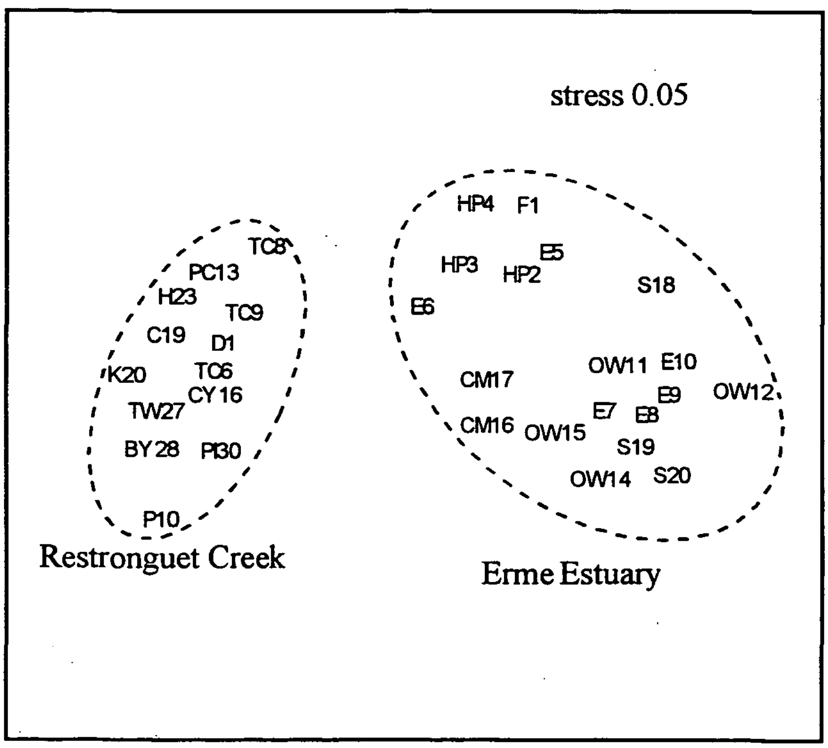


Figure 4.31: Multi-dimensional plot of geochemical data, Restronguet Creek and the Erme Estuary.

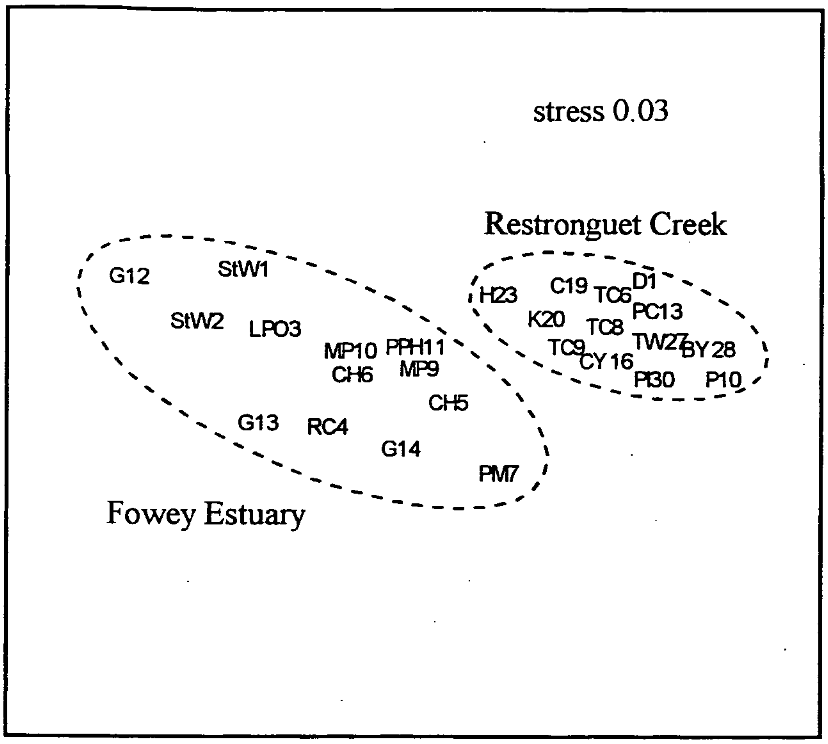


Figure 4.32: Multi-dimensional plot of geochemical data, Restronguet Creek and the Fowey Estuary.

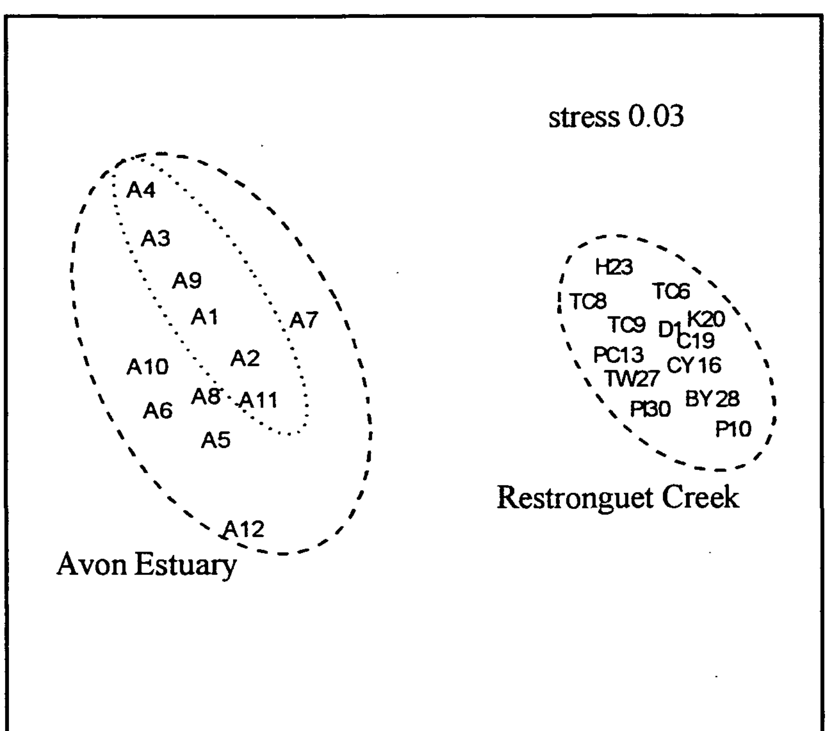


Figure 4.33: Multi-dimensional plot of geochemical data, Restronguet Creek and the Avon Estuary.

The concentrations of metals in each estuary follow a trend which is indicative of the metal mined and the mineralisaton present. Restronguet Creek, for example, has a metal concentration order of Fe>Zn>Al>Cu>As>Pb>Ni>Cd, with Cu and As higher than Pb. The Erme and Avon samples differ in that Pb is, overall, higher relative to Cu (Fe>Al>Zn>Pb>Cu>Ni) with As not detected (Cd was detected in the Erme samples but not in the Avon samples). The Fowey concentration order is Fe>Al>Zn>Cu>Pb>Ni (As and Cd not detected) which differs from Restronguet Creek where Zn has a higher concentration than Al. This may reflect greater Zn extraction from the mines draining into Restronguet Creek, whereas, the drainage of the Fowey River passing through areas dominated by china clay extraction, may account for the relatively elevated levels of Al derived from the mineral lattices of the feldspars and micas. The latter assumption is supported by the high mica content of the Fowey sediments (Section 4.4.5). The detection of As in Restronguet Creek relative to the other estuaries may reflect the long term effects of the processing plant at Bissoe through which locally and nationally derived As was purified (Chapter One, Section 1.5.1). The Erme and Avon samples are similar and place Al second in concentration but Pb is higher than Cu (as a sample mean). This may reflect the change to silver-lead mining from Sn (not detected) and Cu (Chapter One, Section 1.5.1, *ii* and *iv*). The high Cu level at the Avon station A7 may reflect a localised source, e.g. Cu based boat anti-fouling paints or agricultural dressings.

The sediment geochemical results show, therefore, that of the locations sampled the highest metal concentrations were recorded for samples from Restronguet Creek (Appendix 1.1b). Thus the metal concentration order (using averaged data from Restronguet Creek) by location is:

Al, Fe and Ni - Restronguet Creek>Erme> Avon>Fowey.

Zn - Restronguet Creek>Fowey> Erme> Avon.

Cu - Restronguet Creek> Fowey > Avon>Erme.

Pb - Restronguet Creek> Erme>Fowey > Avon.

The relative position of the Fowey data with respect to Cu and Zn may reflect high inputs of these metals derived from a recent orgin (e.g., boat anti-fouling paints). The metals Al, Fe and Ni may have historical sources which are gradually being reduced by the daily dredging of the lower estuary and the generation of increased depth. The Avon reservoir (Figure 1.20) may have a filtration influence which reduces the concentration of metals, in particular Pb, which orginates from the old mines situated above the reservoir or are now submerged within it. The Erme Estuary appears to retain previously accumulated sediment-bound metals.

Comparisons between the water quality data obtained at the Devoran monitoring station and the concentrations of metals in the sediments show good agreement. However, Ni was either not detected in the water or was in very low concentrations. Comparison between the concentrations of metals in the sediment samples and the background levels (Table 4.6) shows that the Restronguet Creek and Fowey data sets exceed the crustal and soil concentrations for the metals Zn, Pb, As and Cd, all of which have been mined in these areas. The concentrations of Al, Fe and Ni are not exceeded. With respect to the Erme and Avon data sets only the Pb and Zn background levels were exceeded and again Pb was economically important to these areas. The Restronguet Creek sediments alone exceed both the crustal and medium soil cocentrations of Cu which are 20 - 90 times greater with respect to average crustal abundances and 30 - 54 times greater than for medium soils reflecting the extent to which this area was influenced by mining.

The averaged data given here for Restronguet Creek is at variance with that of the literature. This is probably due to the different extraction methods applied by each author. The averaged values determined by this research (Table 4.7) are the lowest with respect to Fe, Cu, Pb, Zn and Ni. The value for Cd is closely similar to that of Bryan and Langston (1992) and Luoma and Bryan (1981) who used 1M HCl extraction only with respect to that metal.

Author/s	Method	Fe	Cu	Pb	As	Zn	Cd	Ni
Current work	1M HCl, AAS	7565	602	82	211	1295	1.5	7
Williams *et al.*, 1998	conc. HNO_3, <63µm, ICP-AES	61093	2303	179	-	3312	-	-
Stubbles *et al.*, 1996a	10% HNO_3, AAS	6312	1271	109	117	2975	1.9	18
Somerfield *et al.*, 1994a	conc. HNO_3 1M HCl, AAS,	62780	2412	199	-	4874	2.7	29.9
Bryan and Langston, 1992	conc. HNO_3 <100µm, AAS	49071	2398	341	1740	2821	1.53	58
Thome, 1983	2M HCl conc. HNO_3, AAS	35314 43344	647 1169	208 213	- -	874 1052	- -	- -
Luoma and Bryan, 1981	conc. HNO_3, AAS * HCl, AAS	-	3052	323	-	3542	0.83*	-

Table 4.7: Restronguet Creek, sediment geochemical data comparison between the literature and the current research.

4.7.5 Association between sediment metal concentrations and other variables

i) Restronguet Creek

It is evident from the sediment geochemistry that the Restronguet Creek samples had high concentrations of Fe relative to the other locations although the amount of Fe introduced into the Creek has been shown to vary considerbly (Figure 4.17). Johnson (1986) described the effects of Fe-oxyhydroxide scavenging as a factor which alters the concentration of other metals under the additional influence of varying pH (Sahu and Bhosale, 1991; Bhosale and Sahu, 1991).

The statistical relationship (Table 4.7) between Fe and other metals in the Restronguet Creek samples shows strong positive correlation (>0.70), for example, with the metals Al, As, Zn, Ni and Cu but Fe is only moderately correlated with Pb (0.55).

variable	Fe	Zn	Cu	Pb	As	Ni	‰	°C	fines	OC%
Al	**0.81**	**0.95**	**0.94**	*0.62*	**0.75**	**0.88**	-0.1	-0.47	0.28	-0.48
Fe		**0.82**	**0.79**	*0.55*	**0.72**	**0.76**	0.36	-0.21	-0.007	0.04
Zn			**0.99**	*0.64*	*0.61*	**0.92**	0.03	-0.4	0.26	-0.52
Cu				*0.58*	0.53	**0.90**	-0.03	-0.3	0.26	*-0.64*
Pb					*0.62*	**0.78**	0.29	0.15	0.11	-0.01
As						*0.61*	0.46	-0.15	0.07	**0.74**
Ni							-0.16	0.01	0.11	0.17
‰								0.2	-0.41	*0.67*
°C									-0.23	0.073
fines										-0.23

Table 4.8: Statistical relationship between sediment metal concentrations in Restronguet Creek and salinity, temperature, proportion of fine material and organic carbon content. Strong correlations are shown in bold (<0.7) and significant correlations are in italics (>0.55 - <0.69).

The correlation coefficient matrix (Table 4.8) for Restronguet Creek also shows Al to be strongly correlated with all other metals except Pb which is significant. Organic carbon (0.74) is strongly correlated to As, but is only significantly correlated to Cu, Zn and salinity. Otherwise there is no significant relationship between the other metals and variables. There is a strong negative relationship (-0.71) between the grain size range >16µm - <63µm and the C/N ratio (not shown by Table 4.8), and between the >63µm size fraction and the C/N ratio there is a less than significant positive relationship (0.5). This suggests that nutritional capacity is greatest in sediments comprising higher proportions of material in the range of >16µm - <63µm.

***ii*) The Erme Estuary**

The Erme samples (Table 4.9) do not show an association between Fe and any other metal, but Al is strongly correlated with Cu and Pb. Copper is strongly correlated to Pb but Ni only shows a significant relationship to Al, Fe, Cu and Pb.

variable	Fe	Zn	Cu	Pb	Ni	‰	°C	fines	OC%
Al	*0.57*	*0.58*	**0.88**	**0.96**	*0.57*	**-0.98**	0.04	0.13	-0.16
Fe		0.3	*0.59*	*0.57*	*0.56*	0.11	-0.52	0.33	-0.0002
Zn			0.54	*0.61*	0.08	-0.36	-0.25	0.1	0.1
Cu				**0.85**	*0.69*	0.17	-0.19	0.2	-0.12
Pb					*0.57*	-0.15	-0.04	0.17	-0.18
Ni						0.35	0.07	-0.16	-0.24
‰							0.5	0.15	-0.15
°C								-0.05	-0.23
fines									0.26

Table 4.9: Statistical relationship between sediment metal concentrations, salinity, temperature, proportion of fine material and ogranic carbon content in the Erme Estuary. Strong correlations are shown in bold (>0.7) and significant correlations are in italics (>0.55 - <0.69).

Salinity has a strong, negative correlation to Al (-0.98) but all other variables are insignificant. This relationship between Al and salinity probably reflects the lower Al concentrations in the lower estuary where salinity is highest (stations S20 and E10). The relationship between salinity and temperature is almost positively significant. There is no statistical relationship shown between grain size and the C/N ratio for any of the control estuaries.

iii) The Fowey Estuary

There is a similar positive correlation shown by the Fowey samples (Table 4.10) relative to Restronguet Creek, with Zn, Cu, Al, Ni and Pb strongly correlated to Fe. Nickel is strongly correlated to Al, Cu and Pb, and Cu is strongly correlated to Zn and Pb. Nickel is the only metal to have a strong correlation to the proportion of fines. Salinity and temperature are strongly correlated to each other.

variable	Fe	Zn	Cu	Pb	Ni	‰	°C	fines	OC%
Al	**0.93**	*0.65*	*0.69*	*0.62*	**0.77**	-0.03	0.02	0.38	0.5
Fe		**0.82**	**0.76**	**0.78**	**0.75**	-0.2	-0.14	*0.55*	0.38
Zn			**0.98**	*0.68*	*0.66*	-0.1	-0.23	0.2	0.2
Cu				**0.75**	**0.75**	-0.03	-0.14	0.27	0.15
Pb					**0.78**	0.29	0.29	0.47	0.35
Ni						0.12	0.0006	**0.75**	0.12
‰							**0.9**	-0.25	0.1
°C								-0.11	0.35
fines									*0.57*

Table 4.10: Statistical relationship between sediment metal concentrations and salinity, temperature, proportion of fine material and ogranic carbon content in the Fowey Estuary. Strong correlations are shown in bold (>0.7) and significant correlations are in italics (>0.55 - <0.69).

iv) The Avon Estuary

The Avon samples (Table 4.11) show strong positive correlation between Fe and Al, and Cu and Zn, which are approaching unity (0.995). All other metals are weakly correlated with Fe. Organic carbon and fines are each significantly correlated to Al. There is only a significant correlation shown between salinity and Al. This is probably due to the erratic distribution of this element.

variable	Fe	Zn	Cu	Pb	Ni	‰	°C	fines	OC%
Al	**0.84**	0.31	0.25	0.52	*0.67*	*0.63*	0.49	-0.48	*0.66*
Fe		0.4	0.37	*0.61*	*0.64*	0.4	0.35	*-0.59*	0.38
Zn			**0.995**	0.41	0.12	0.42	0.22	-0.36	0.15
Cu				0.41	0.05	0.42	0.18	-0.32	0.1
Pb					0.25	0.24	0.13	-0.19	0.27
Ni						0.12	0.27	-0.32	0.33
‰							0.42	-0.28	-0.2
°C								*-0.5*	0.32
fines									-0.04

Table 4.11: Statistical relationship between sediment metal concentrations and salinity, temperature, proportion of fine material and ogranic carbon content in the Avon Estuary. Strong correlations are shown in bold (>0.7) and significant correlations are in italics (>0.55 - <0.69).

4.7.6 Summary

The strong positive correlation of certain metals with Fe indicates that the scavenging activity of Fe as a hydrated oxide may have taken place and a common fate is suggested (Sahu and Bhosale, 1991; Bhosale and Sahu, 1991). Metals which are preferrentially scavenged by Fe to form hydrated complexes are considered to be highly stable and less available to an organism but this is pH dependent (Johnson, 1986; Milam and Farris, 1998). This has important implications with respect to the acidified environment of Restronguet Creek as the bioavailability of metals is not always correlated with sediment metal concentrations under neutral pH conditions (Boon *et al.*, 1998; Leppanen *et al.*, 1998). The lack of an association between the proportion of fine material (<16μm) and metal concentration with respect to Restronguet Creek may be due to over-saturation in metal loading to available binding sites (Luoma and Bryan, 1981), or that the fine material is overwhelmingly anthropogenicaly derived from the mill at Wheal Jane. The relationship between fines and Fe and Ni in the Fowey samples is significant, indicating that metal absorption to sediment surfaces may be a minor influence. In general, the control estuarine data are more dissimilar in that Al is strongly correlated with Cu in the Erme and Fowey but not in the Avon set, although the latter showed a weak correlation between Al and Zn.

Chapter Five

Foraminiferal Response to Changes in their Environment: Results

5.1 Introduction

As with most organisms foraminifera are known to respond to changes in their environment and their responses (standing crop density, diversity, species dominance and distribution and test deformity) may be used to evaluate both natural and anthropogenic influences. Buzas (1969) and Ellison and Peck (1983), for example, used standing crop density or the absence of living foraminfera as indicators of anthropogenic deleterious effects. Similarly, measures of diversity have been used as indicators of environmental stability by the use of various indices which have been applied to both micro-, meio- and macro-fauna (Bates and Spencer, 1979; Washington, 1982; Sommerfield *et al.*, 1994a,b; Austin *et al.*, 1994; Stubbles *et al.*, 1996a, b). Species distribution and, specifically, the absence of certain key species either in particular zones or throughout a location (in anticipation that they should be there) has been used as an indication of environmental perturbation (Greiner, 1969; Schafer and Cole, 1974; Schafer, 1982; Ellison *et al.*, 1986; Alve and Bernhard, 1995). In contrast, changes in species dominance may also be an indicator of modifying influence (Murray, 1979a; Schafer *et al.*, 1995). The proportion of tests showing deformity can provide an important numerical division between effects caused by naturally occurring variables, for example, changes in temperature (Chang and Kaesler, 1979; Stouff *et al.*, 1999) and the introduction of pollutants (Sharifi *et al.*, 1991; Alve, 1995a). Acid etching of tests has been shown to be an indicator of acid mine drainage and reducing environments (Alve and Murray, 1995b; DeRijk, 1995;

Stubbles *et al.*, 1996a) with the weakening of the tests leading to enhanced loss of test material (Stubbles *et al.*, 1996b).

This chapter summarises the results of the foraminiferal analysis in the heavily polluted Restronguet Creek and the relatively unpolluted estuaries of the Fowey, Erme and Avon using these various responses as indications of deleterious effects.

5.2 Foraminiferal standing crops

5.2.1 Foraminiferal non-colonisation

i) Restronguet Creek

During the initial period of sampling in the autumn of 1992 the upper Creek stations D1, C19 and K20 were not colonised by foraminifera (Table 5.1). Station H23 has occasionally been barren between winter 1993 and spring 1994, but since the summer of 1994 foraminifera have consistently colonised this station. The period of non-colonisation at stations D1 and C19 was between autumn 1992 and winter 1993, and was followed by a paucity of stained individuals (Appendix 2.1 and Table 5.1).

SEASON AND YEAR OF SAMPLING									
station	**A92**	**W93**	**SP93**	**S93**	**A93**	**W94**	**SP94**	**S94**	**A94**
D1	-	-	+	+	+	-	-	+	+
C19	-	-	+	+	+	-	-	+	+
K20	-	-	-	-	-	-	-	-	+
H23	+	-	+	+	+	-	-	+	+
BY28	-	+	+	+	+	+	+	+	+

Table 5.1: Periods of colonisation (+) and non-colonisation (-) during 1992 - 1994 in Restronguet Creek. A = autumn, W = winter, Sp = spring and S = summer.

At stations D1 and C19 a second period of non-colonisation occurred during winter and spring 1994. Station K20 has had a longer period of absence relative to the other sample stations and was barren from the onset of sampling (autumn 1992) until autumn 1994 when a small standing crop of 52 stained individuals was recorded. Sample station BY28 was barren on only one occasion (Table 5.1).

ii) Erme Estuary

Station F1 (Chapter One, Figure 1.15) has never been colonised throughout the period of sampling and this may reflect both the lack of a suitable substrate (Stubbles, 1995) and low salinity (Chapter Four, Section 4.3.3). The other Erme sample stations showing occasional absence (Table 5.2) of foraminifera were HP2 (winter and summer of 1993), HP3 (spring and summer of 1993) and HP4 (summer 1993). For the other seasons these stations showed an impoverished standing crop relative to the other estuary stations (Appendix 2.2).

SEASON AND YEAR OF SAMPLING				
stations	**W93**	**SP93**	**S93**	**A93**
HP2	-	+	-	+
HP3	+	-	-	+
HP4	+	+	-	+

Table 5.2: Periods of colonisation (+) and non-colonisation (-) in the Erme Estuary. Station F1 is not included as it was continually barren. A = autumn, W = winter, Sp = spring and S = summer.

5.2.2 Standing crops - spatial distribution

i) Restronguet Creek

Due to the complexity of the standing crop data (the raw data are given in Appendix 2.1) the seasonal data sets for each station have been combined and averaged to produce annual means (AM). This smoothing of the variation has made the trends more easily identifiable.

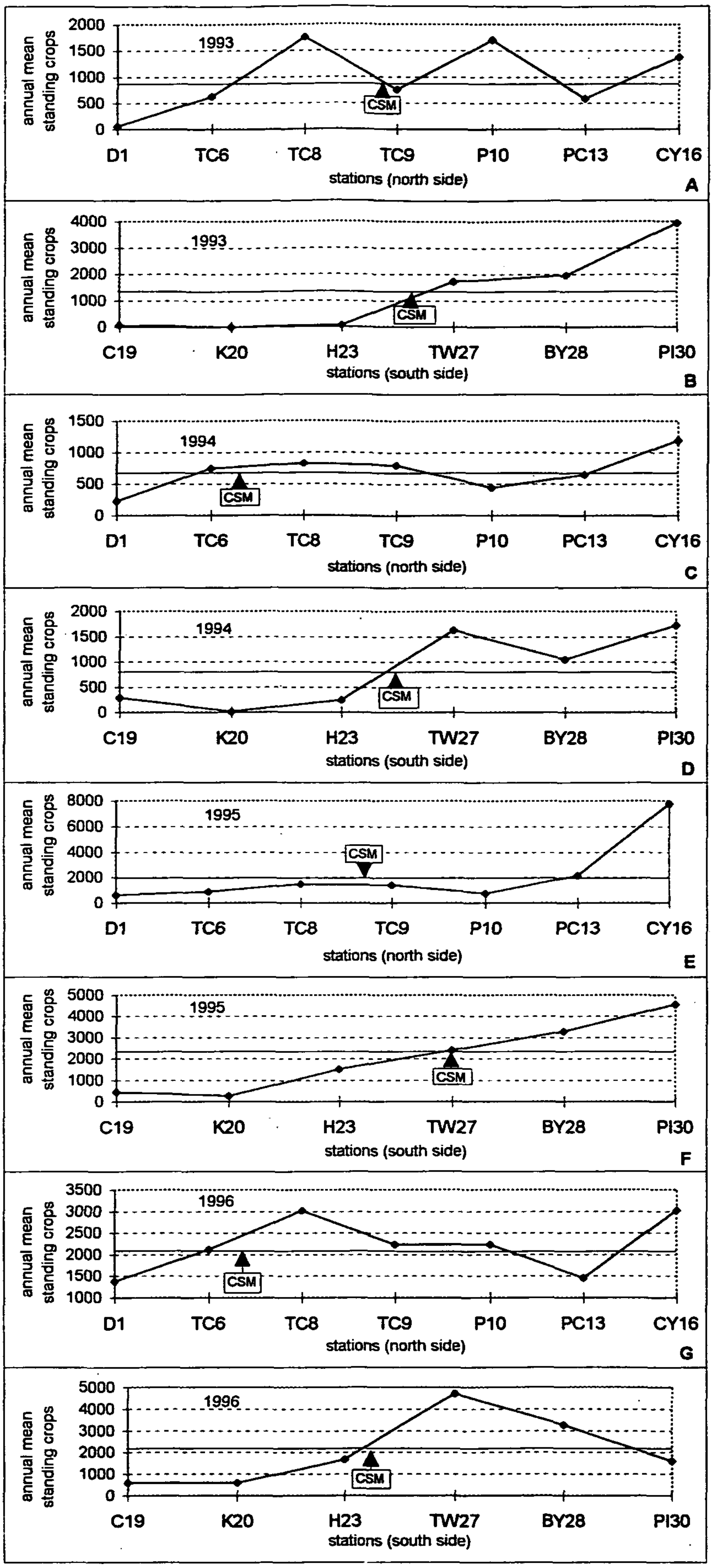


Figure 5.1: Annual mean standing crop density, Restronguet Creek. a) 1993 north side, b) 1993 south side, c) 1994 north side, d) 1994 south side, e) 1995 north side, f) 1995 south side, g) 1996 north side and h) 1996 south side. CSM denotes combined sample mean.

With respect to Restronguet Creek there are four AM standing crop groups (1993 - 1996). In addition, the combined sample mean (CSM) is also used to show those sample stations which are either below or above the CSM and was calculated from the AM given above. Variation with season is given in Section 5.2.3.

Generally, the upper sample stations in Restronguet Creek (D1, C19 and K20) were characterised by smaller standing crop densities ranging between a few (<10) and less than 2000 relative to the stations in the mid- to lower Creek which show a difference of between one and two orders of magnitude (Figure 5.1, a - h). Furthermore, the upper Creek stations have consistently had standing crop densities which fall below the mean of the combined samples (CSM). On only a few occasions is a linear trend shown whereby there is an incremental increase in the standing crop density with distance down the Creek (Figure 5.1, b, d and f). The south side of the Creek provides only two examples of a gradual, smooth trend (1995 and to a lesser extent 1993, Figure 5.1, f and b) with all other examples being unpredictable. Comparison of the mid - Creek stations, TC6, TC8, TC9 and P10, with the respective lower sample point, station CY16, show only a weak linear trend and the profile is erratic with respect to Figure 5.1a. Stations P10 and PC13 (Figure 5.1, a, c, e and g) generally had lower standing crops relative to the other stations and, with respect to PC13, this may reflect the high position at the head of Penpoll Creek. Data obtained in the last year of analysis show that the mid - Creek stations had densities similar to or larger than those standing crops at the lower Creek stations BY28, PI30 and CY16 (Figure 5.1, g and h). Marked differences in standing crop densities between the north and south sides of the Creek are evident. The standing crop densities on the north side were usually less than those recorded for the south side with the exception of the 1995 data when the maximum standing crop on the north side was >3000 greater than that of the south side (Figure 5.1, e and f). This anomaly was particularly evident with respect to stations TC6 - CY16 relative to TW27 - PI30 and may be due the very dry summer of 1995 which, for that year, saw a reduced discharge from Wheal Jane, in addition to reduced water flow through the other disused mines (Chapter One, Section 1.5.1, *i*, Figure 1.7). Prior to 1995 the dilution effects of the River Kennell on the south side, which is relatively uncontaminated, may have reduced any impact from the Carnon River Valley mines and, hence, leading to higher standing crop densities during this period at stations TW27 - PI30. In addition, there is the distinct difference in commercial and residential activity (both present and historical) between the north and south sides of the Creek, with greater activity associated with the north side of the Creek.

***ii*) The Erme Estuary**

For each of the control estuaries, which were sampled for one year each, there is one AM group. The Erme Estuary standing crop data did not show a smooth, gradual trend and the profile is unpredictable (Figure 5.2, a and b). Stations HP2, HP3 and HP4 produced the smallest standing crops (Appendix 2.2) and are consistently below the combined sample mean (CSM). Stations E5, E6, E7, S18 and OW14 (Figure 5.2, a and b) show moderately high standing crop densities ranging between 1000 and 2300. The lower estuary station E10, on the west side, was unusual with an annual mean (AM) standing crop density which was less than the upper stations HP3 and HP4. Sample station E8 within the saltmarsh at Efford was the most productive area with the highest annual mean standing crop, and the other saltmarsh stations E7 and OW11 were second and third in standing crop density respectively.

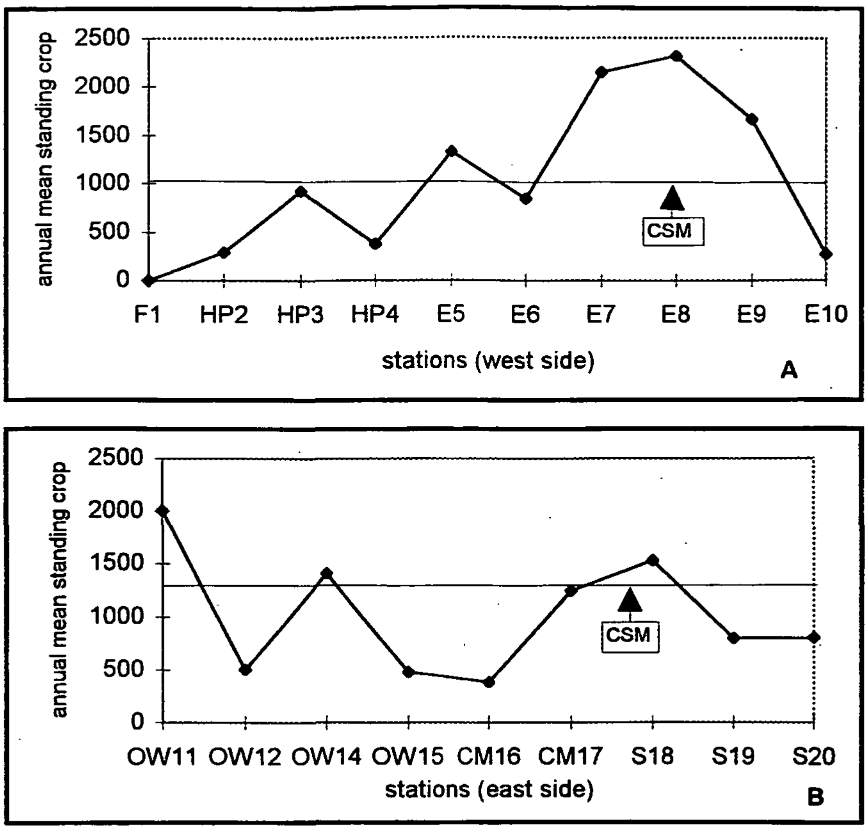


Figure 5.2: Annual mean standing crop densities, Erme Estuary, 1993. a) west side and b) east side. CSM denotes combined sample mean.

***iii*) The Fowey Estuary**

All stations on the Fowey Estuary (Appendix 2.3) were colonised (spring 1994 to winter 1995) but the subsidiary creek stations LPO3 and RC4 had the lowest standing crop densities (annual means) of 55 and 272 respectively (Figure 5.3a) and fall below the combined sample mean. The main channel stations StW1 and StW2 generally had lower standing crops relative to the mid - low estuary stations but were similar to stations PM7 and MP9 (Figure 5.3a). Despite averaging to smooth seasonal variation, a distinct trend on the east side, whereby the standing crop density increased incrementally from the upper to the lower estuarine samples (Figure 5.3a) is not a feature and the profile is unpredictable. The sharp decline at creek stations LPO3, RC4 and, to a lesser extent at, PM7 and PPH11 may reflect the variable environmental conditions of lower salinity and temperature relative to the main channel stations. The west side of the estuary shows a smooth trend but this is probably an artifact of the limited sampling points (Figure 5.3b).

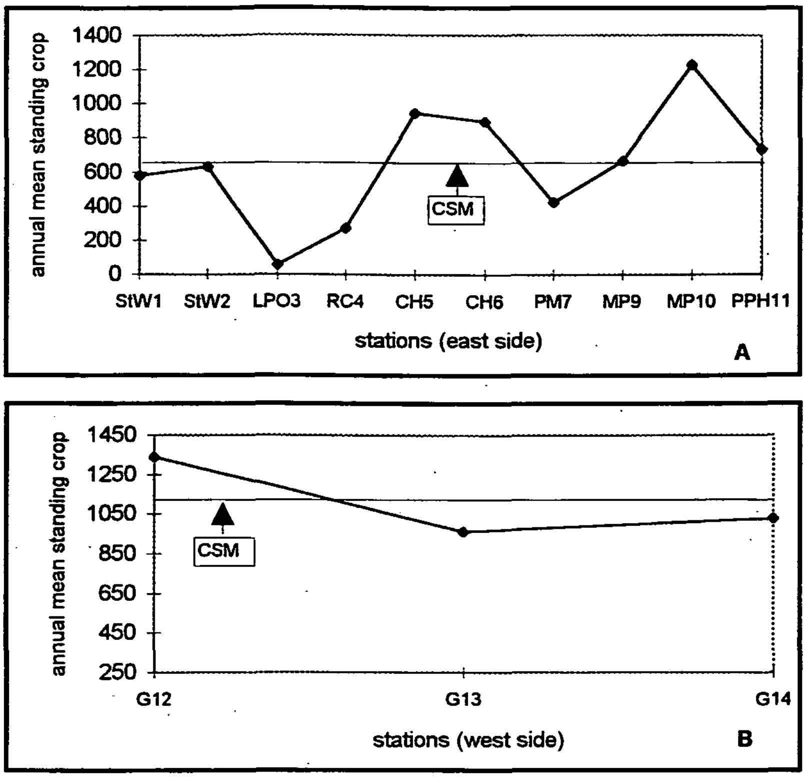


Figure 5.3: Annual mean standing crop densities, Fowey Estuary. a) east side and b) west side. CSM denotes combined sample mean.

iv) The Avon Estuary

All the Avon sample stations (Figure 5.4, a and b) were colonised by foraminifera (summer 1995 to spring 1996) but the upper estuary samples A1 (937), A2 (753), A9 (1001) and the mid - estuary station A5 (1132) produced only small standing crops relative to stations A3, A4, A6, A7, A8, A10, and A11 further down the estuary (Appendix 2.4) and are consistently below the CSM shown on Figure 5.4, a and b. The Avon samples show an irregular standing crop distribution, particularly on the west side and a linear trend is only shown between stations A5, A10 and A11 on the east side (Figure 5.4b). The saltmarsh station A11 (8669) and, to a lesser extent, A3 and A7 (Figure 5.4a) had the highest standing crops with the lower estuary stations A8 and A12 having the lowest. This is similar to that found for the Erme

Estuary.

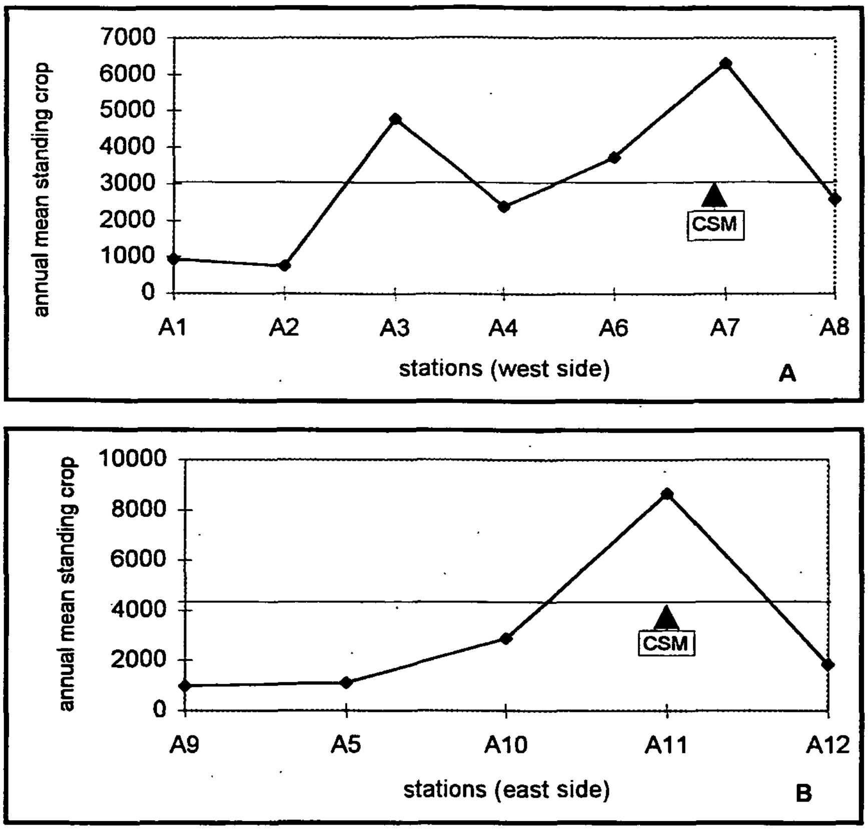


Figure 5.4: Annual mean standing crop densities, Avon Estuary. a) west side and b) east side. CSM denotes combined sample mean.

5.2.3 Standing crops - Seasonal variation

***i*) Restronguet Creek**

Analysis of the seasonal data (non-averaged) shows that for the period autumn 1992 to summer 1993 (inclusive) the highest standing crop densities were obtained in the spring and lowest in the autumn and winter (Figures 5.5, a - g, and, 5.6, a - f). The exception to this is shown by stations TC6 and TC8 (Figure 5.5, b and c) in which the summer abundances were greater. Since summer 1994 the summer samples had, generally, provided the highest standing crop densities. All stations in spring 1994 had very low standing crops relative to 1993 and subsequent years. At this time (spring 1994) the upper Creek stations, D1, C19, H23 and K20 were barren.

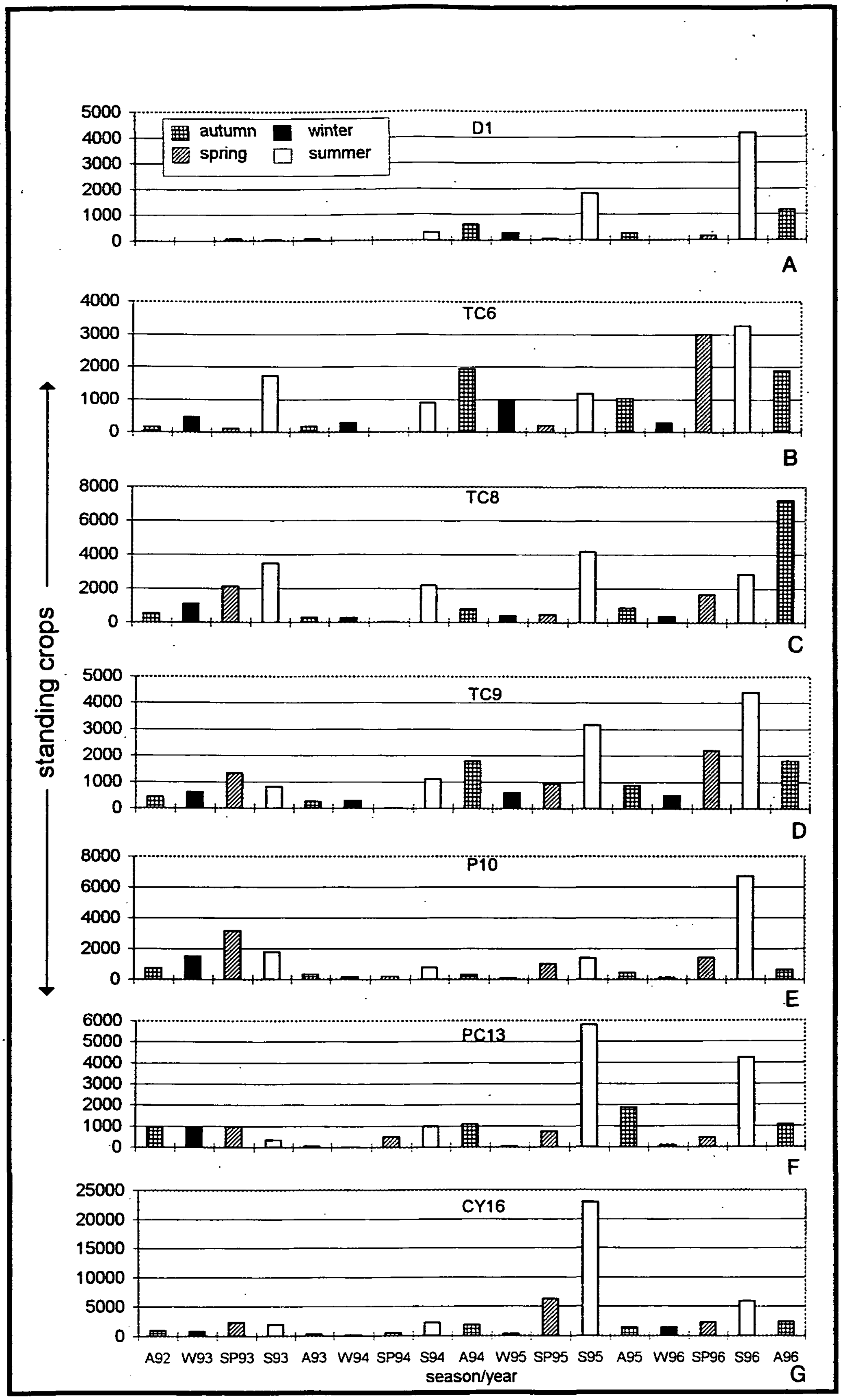


Figure 5.5: Seasonal and annual standing crop, Restronguet Creek. North side stations D1 - CY16 (a - g).

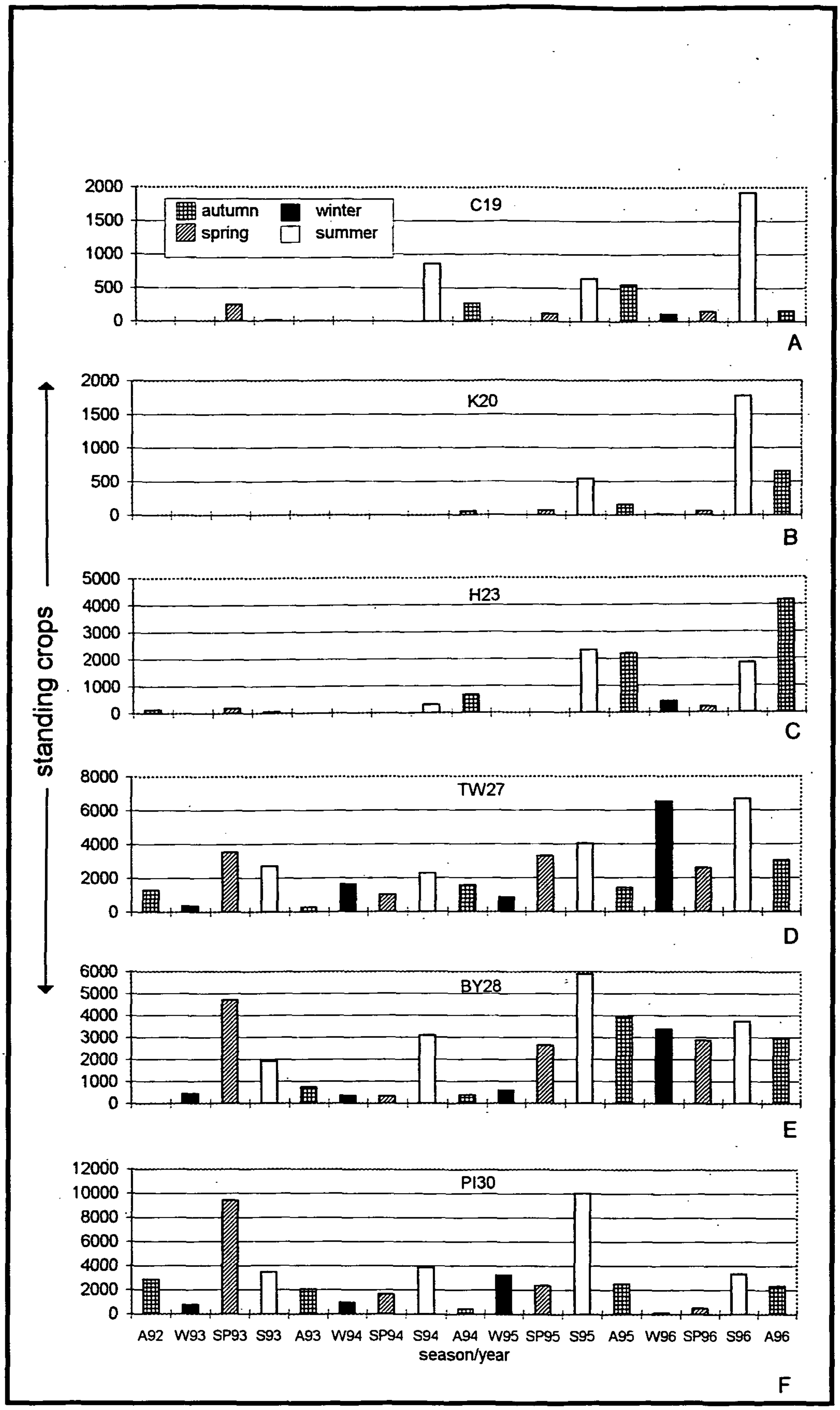


Figure 5.6: Seasonal and annual standing crops, Restronguet Creek. South side stations C19 - PI30 (a - f).

Stations BY28 and PI30 (Figure 5.6, e and f) clearly show the greatest difference between seasonal standing crop densities, whereas stations D1, TC6, PC13, CY16 C19 and H23 show strong similarity between the seasons with few exceptions before spring 1994 (Figures 5.5 and 5.6). Generally, the summer abundances were higher than for winter on the north side of the Creek. The seasonal data from the south side are less clear but in only two cases (H23 and K20) was the summer standing crop density less than in the autumn (Figure 5.6, c and b). The upper Creek stations C19 and K20 have summer abundances greater than the autumn with the spring and winter having very similarly low values (Figure 5.6, a and b). The summer standing crop densities at station TW27 (Figure 5.6d) were usually greater with the exception of winter 1996 which was almost equal to summer 1996.

***ii*) The Erme Estuary**

The winter, summer and autumn Erme samples (1993) had low standing crops relative to the spring which had the highest (Figure 5.7, a and b). The exceptions to this were stations E8, E10, OW12 and S19 at which the summer densities were highest. The winter and autumn samples from stations E9, OW12, S18, S19, and S20 had similar standing crop densities and at E7 the summer, autumn and winter were also closely similar to each other. At only four other stations is there a similarity between seasons; E10 (summer and spring), CM16 and CM17 (spring and winter) and at station E6 (summer - winter). Overall, the lower estuary stations E10 and S20 had standing crop densities, during each season, which were less than those found at the mid - estuary stations (Figure 5.7 a and b). The coarser sediment present, particularly at station S20 (Chapter Four, Figure 4.10b) may account for this as sandier substrates indicate higher velocities which are preferentially avoided by the foraminifera (Murray, 1991). In addition, muddier sediments are associated with higher organic loadings and nutrition (Lidz, 1965; Buzas *et al.*, 1989; Warwick *et al.*, 1995).

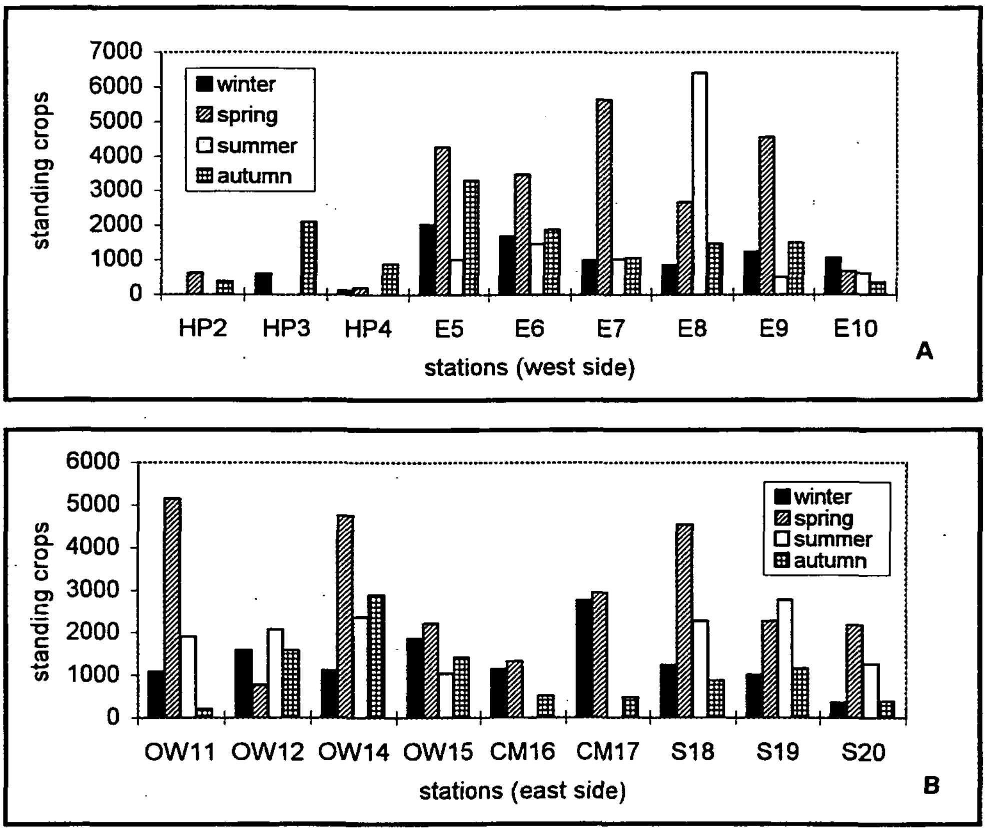


Figure 5.7: Seasonal standing crops, Erme Estuary. a) west side and b) east side.

iii) The Fowey Estuary

Analysis of the Fowey data suggests that this estuary is strongly influenced by seasonal variation, with the seasons showing little regularity, whereby the same trend at each station is shown (Figure 5.8, a and b). The winter produced the lowest standing crop densities at stations LPO3, CH5, CH6, MP10 and at G14 but at stations StW1 and PM7 the winter standing crop densities were highest (Figure 5.8, a and b). The mid - estuary station CH6 and the lower estuary stations MP10 and G14 show the clearest seasonal separation and in the same order as follows:

spring>summer>autumn>winter

Similarity between seasons for each sample station is unusual and is confined to the upper estuary and creek stations StW2 (winter and spring), LPO3 (winter and spring/autumn), PPH11 (autumn and winter) and the mid- and low estuary stations CH5 (spring and summer) and MP9 (winter and autumn).

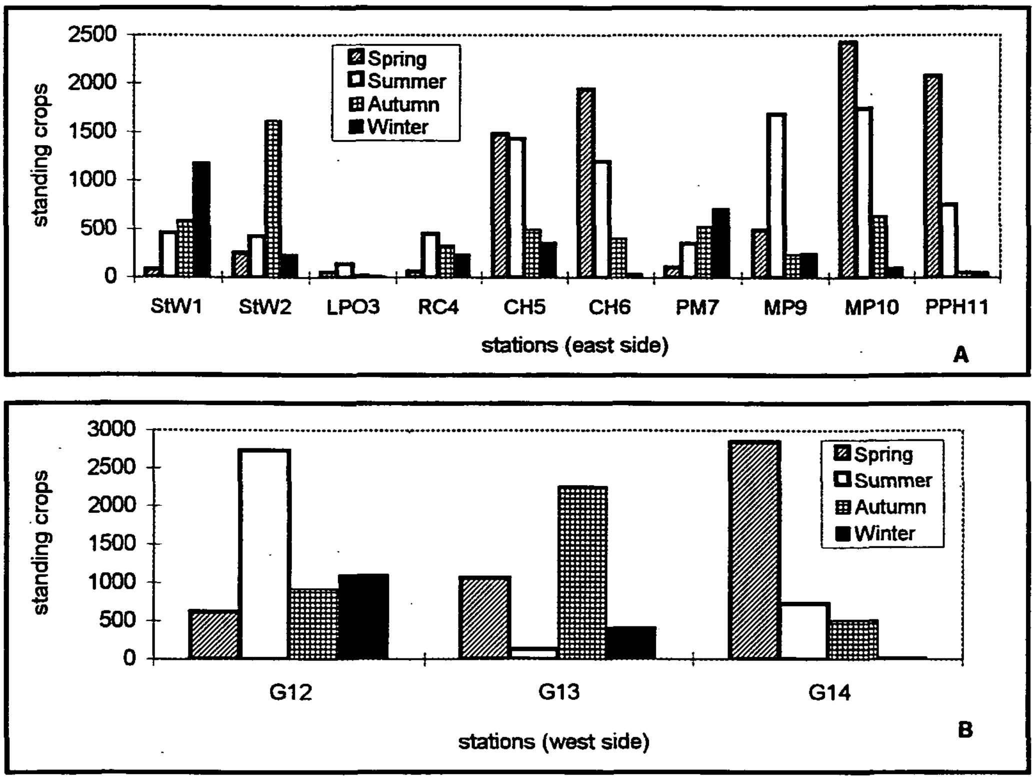


Figure 5.8: Seasonal standing crop, Fowey Estuary. a) east side and b) west side.

iv) The Avon Estuary

Overall the summer produced the highest standing crop densities (except at stations A4 and A7) on the west side of the estuary (Figure 5.9a). Summer densities were high on the east side at station A11 and apart from station A9 (lowest densities in the summer) lowest densities were recorded in the spring with the highest densities in the autumn and winter (Figure 5.9b). Sample variation between the seasons is very high and only the upper estuary and creek stations show a similarity between the seasons A1 (winter and autumn), A2 and A3 (spring and autumn) and at station A5 (summer and autumn). This may be due to the extreme weather conditions prevailing during this period of sampling. The summer of 1995 was a drought year and winter 1996 was particularly cold, the effects of which may have delayed the spring standing crop bloom in 1996 (Chapter Four, Section 4.2.4).

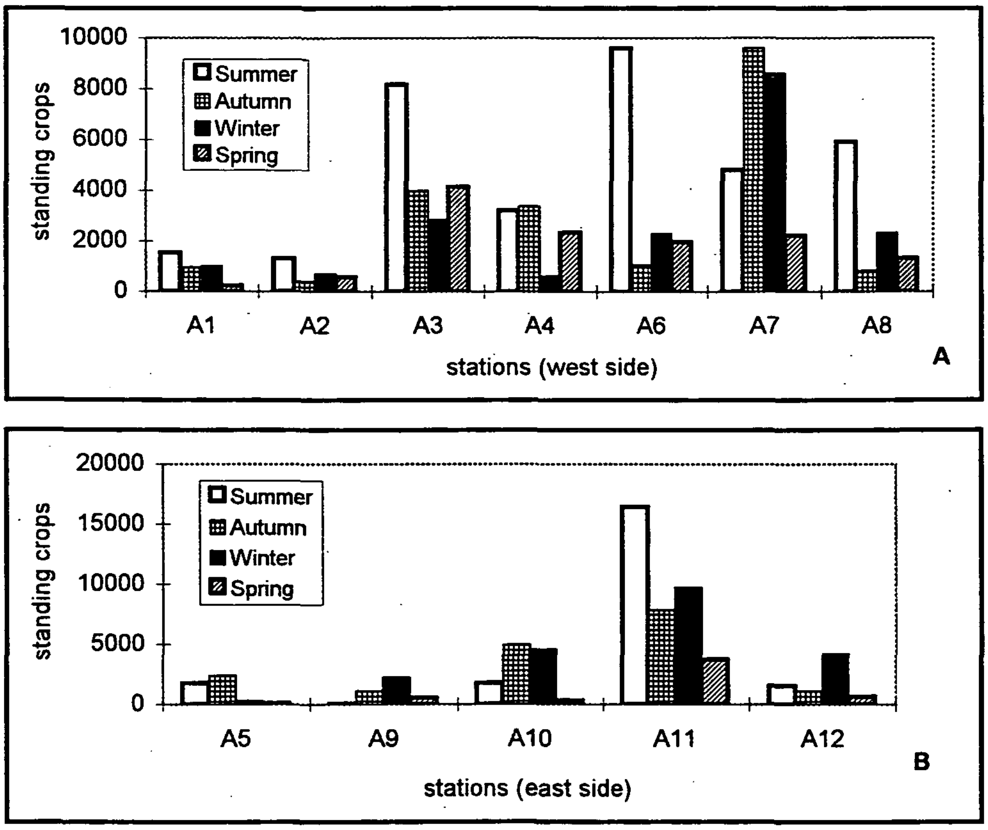


Figure 5.9: Seasonal standing crop, Avon Estuary. a) west side and b) east side.

5.2.4 Standing crops - Annual variation in Restronguet Creek

Annual changes in colonisation and increased standing crop densities have been recorded at each station in Restronguet Creek (Figure 5.5, a - g and Figure 5.6, a - f). The most notable changes have occurred at D1, C19 and K20. In between the initial barren periods the standing crops recorded at station D1 remained below 100 (Figure 5.5a) and, following the second barren period, standing crops increased only intermittently and remained highly variable with the 1996 winter and spring densities only marginally greater than for 1993. Station C19 (Figure 5.6a) produced a standing crop density of 245, 18 and 16 between the barren periods but has produced greater densities with a more stable trend compared with D1. Station K20 (Figure 5.6b) has shown a more erratic standing crop due mainly to intermittent colonisation but in most cases the 1996 abundances are substantially greater than the preceding year. With the exception of stations D1and TC9 (summer only) a strong linear relationship between an increase in standing crop density per station with time is not evident. For the other stations, the initial standing crops were in the low hundreds. The exception to this is station TW27 in the autumn, which had a standing crop density of 1280 in 1992 and in 1996 increased to 3056. Station PI30, shows an overall increase between the autumns of 1992 and 1996. All the other stations have, given variation with season, risen above 1000. The greatest increase is shown by the summer seasonal sets, the values for 1995 being particularly high at stations PI30 (10048) and CY16 (22976). This was coincidental with an exceptionally prolonged hot summer. Station PI30 has remained, however, relatively stable at <4000 (with the exception of spring 1993 and summer 1995; Figure 5.5m). By disregarding the major peak of summer 1995, it is evident that in general the standing crop densities in 1996 were higher than those recorded for 1992/93 (comparing season with season), but densities were less in 1996 relative to the preceding year for most sample stations.

5.2.5 Relationship between standing crop and other variables

i) Restronguet Creek

Correlation coefficient analysis carried out between standing crop and corresponding salinity data shows there to be a positive relationship between these two variables (Tables at the end of Chapter Five). The summer and spring correlation coefficients are, in all cases significant and range between 0.60 and 0.84 in the summer and between 0.59 and 0.81 in the spring. The relationship is less strong with respect to the autumn and winter and probably reflects non-colonisation, at certain stations, during these seasons in 1992, 1993 and 1994. Overall, therefore, foraminiferal abundances appear to increase with increasing salinity, particularly in the spring and summer (Table 5.3). The seasonal correlation values have occasionally varied year by year, reflecting changes in standing crop density, but not salinity which did not alter markedly between years. This was more pronounced in the autumn which had two occurrences of below significant levels (1994 and 1996).

In general, significant relationships between standing crops and temperature were not consistent, particularly for spring and autumn (Table 5.3). The strongest anomalies were detected during the winter but most particularly for the summer which were all significant.

The correlation coefficients between standing crop densities and percentage carbon (Table 5.3) are generally insignificant (<0.39) with the exception of autumn and summer 1996 (-0.64 and 0.62 respectively). The same applies to the C/N ratio and all show a negative and insignificant (<-0.3) correlation. The random distribution of negative and positive correlation coefficients precludes a predicable trend which suggests that these two parameters are unlikely to influence foraminiferal standing crops. Any significant and strong relationships appear to be coincidental.

There are no significant correlation coefficients shown between the three sediment grain size categories and standing crop densities (Table 5.4). Of the three categories, the 16µm category is the only one to show a negative relationship with standing crop (-0.3).

Between the years 1992 and 1994 there are no significant correlations shown between the metals and standing crops (Tables 5.5, a - e). In 1995, however, Al, Cu and Zn show a negatively significant relationship with standing crop. The metals are negatively correlated and show the least variation in 1996. With the exception of

1993, Al and Ni are negatively correlated with standing crop. The correlation coefficients show little numerical consistency and this would suggest that sediment-bound metals have a low level of association with the standing crop densities.

***ii*) The Erme Estuary**

The Erme standing crop densities do not appear to be strongly influenced by salinity, temperature, percentage carbon, the C/N ratio and metals. For each of these variables the correlation coefficients are insignificant for every season (Table 5.6). The autumn salinity, temperature and C/N values are particularly low and are approaching neutral. Each of the sediment grain size categories show an insignificant relationship with standing crop. The correlation coefficients between metals and standing crop also show an insignificant relationship (Table 5.7). With the exception of Ni, each metal is positively correlated. It is evident, therefore, that standing crop densities vary independantly of these parameters and are controlled by other factors; e.g., patchy distribution (Lynts, 1966; Murray, 1991).

***iii*) The Fowey Estuary**

The correlation coefficient analysis shows the relationship between standing crop and salinity (Table 5.8) is significant with respect to the spring (0.57) but less so for summer, and weak for the autumn and particularly the winter (0.35 and 0.14 respectively). Standing crop densities, therefore, appear to be only moderately influenced by salinity in the summer and spring.

The Fowey data demonstrate a strong correlation with respect to temperature and the spring and summer standing crops (0.83 and 0.87 respectively). The winter of 1995 shows a near neutral, negative score of -0.1 (Table 5.8).

Coefficient analysis shows that percentage carbon and the C/N ratio are not significantly correlated with the standing crop data (Table 5.8). With respect to the sediment grain size categories (Table 5.8) there are also no significant correlations, the highest being for the 16µm category (-0.47).

Moderately significant, negative correlations are shown between standing crops and the metals Cu and Zn of -0.5 and -0.55 respectively (Table 5.9). All other metals are also negative but are insignificant, with Pb approaching neutral.

***iv*) The Avon Estuary**

It is apparent that there is little significant association shown between salinity, temperature, percentage carbon and the C/N ratio with the standing crop densities (Table 5.10). With the exception of winter salinity (0.53) and the spring C/N ratio (0.5), the correlation coefficients are all less than 0.44 and hence, insignificant.

The correlation coefficient analysis (Table 5.10). shows only the sediment grain size category >16 - ≤63µm to have a strong, positive relationship with standing crop densities (0.73). The metals Cu and Zn (0.65 and 0.61) are positively and significantly correlated with standing crop (Table 5.11) which is dissimilar to that shown by the Fowey data. Nickel shows the only negative relationship, which is similar to the Erme Estuary.

5.3 Diversity

5.3.1 Introduction

The two most common measures of diversity which are used in micropalaeontological studies are the Fisher Alpha Index (Fisher *et al.*, 1943) and the Shannon-Weiner Information Function, H(S) where H is the information theory and S is the number of species (Washington, 1982). High or low, (in relative terms) diversity can be a measure of the stress levels in an environment and species living on the edge of their tolerance limits with respect to abiotic and biotic variables will form low diversity assemblages (Alve and Murray, 1995a).

5.3.2 Species diversity

***i*) Restronguet Creek**

In Restronguet Creek the three calcareous species *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia beccarii* are present but the agglutinating species *Miliammina fusca*, *Jadammina macrescens* and *Trochammina inflata*, are absent. These six euryhaline species form typical assemblages and are commonly found in estuaries and saltmarshes (Murray, 1991; Stubbles, 1995; Hayward *et al.*, 1996). The Fisher Alpha Indices for all sample locations have scores below 0.7. Restronguet Creek shows a trend whereby the lower values of H(S) below 0.75 are commonly found in the upper Creek areas, for example, stations D1, C19 and K20. At these stations dominance by a particular species has been more pronounced and possibly reflects restricted environmental conditions which may favour one species over others (Alve and Murray, 1995a). The very low values of 0.1 which occur in all the estuaries, correspond to single species proportions >90% with the remainder of species accounting for <10% (Section 5.4.2). Zero scores correspond to monospecific assemblages and also occur in all the estuaries. Higher values $\leq$ 1.09 (e.g., CY16 autumn 1993) correspond to a more even distribution between two species having similar values (in this case 45% each) and which has reduced the influence of a single minor species. In general, diversity indices for Restronguet Creek have increased since 1992, the values for the summer of 1996 all being above 0.7 (initial values 0 to 0.15), and most above 1.0. Diversity remains unchanged but the rise in species equitability has been produced by the increased abundance of *A. beccarii* which was a minor species between 1992 and 1994 (Section 5.4.2).

***ii*) The Erme Estuary**

The six species *Miliammina fusca*, *Jadammina macrescens*, *Trochammina inflata*, *Haynesina germanica*, *Elphidium williamsoni* and *Ammonia beccarii* (Chapter Three, Plates 1-4) were present in samples taken from the control estuaries but the Fisher Alpha Index remains less than 1.0. These six species were not found colonising all sample areas in the control estuaries as a complete assemblage, but formed discrete zones (Section 5.4.2, *ii*). This species zonation can be defined by single species predominance, whereby one species is more abundant than any other and this accounts for the lower H(S) values. The Erme samples had H(S) values as low as 0.15 but the occurrence is infrequent with a greater number of high values exceeding 0.98, particularly for the summer and autumn. These lower values correspond to samples taken from the high estuary stations HP2, HP3 and HP4 (0 - 0.45). Overall, the Erme Estuary samples yielded higher H(S) values relative to Restronguet Creek for the same period.

***iii*) The Fowey Estuary**

The samples from the Fowey Estuary showed similar diversity indices, whereby the lower values of H(S) were recorded for the high estuary station StW2 (<0.98), the uppermost subsidiary creek station LPO3 (<0.45) and the lower creek station PPH11 (0.99). Samples from the two mid - estuary stations, CH5 and CH6, showed lower values in spring and summer corresponding with the high species dominance of *H. germanica* (Section 5.4.2, *iii*). However, for the Fowey Estuary samples the values of H(S) are only moderately higher than those obtained for Restronguet Creek for the same period.

iv) **The Avon Estuary**

The Avon Estuary samples also yielded low values of H(S) from the upper estuary stations A1 and A2 (0 - 0.78) and, occasionally, A9 (0 - 1.75). The higher value obtained was due to a more even distribution between *E.williamsoni* and *M. fusca* (Section 5.4.2, *iv*). In the majority of cases, in the mid - to low estuary, however, the Avon samples had high H(S) values >1.0 and for the same period are greater than those from Restronguet Creek. None of the control estuaries, however, produced values greater than 1.75 and the upper estuary values were comparable to those from similar sample locations in Restronguet Creek.

5.3.3 Summary

In summary, the variation in the indices H(S), can be due to a number of environmental controls (Alve and Murray, 1995a) generally leading to high diversity assemblages with low dominance or low diversity assemblages with high dominance. Values of the diversity index H(S), therefore, may be high at stations with few but evenly distributed species. Lower values may be obtained from samples from such stations if additional species occurring in low abundance are also included; i.e., there is a weighting effect. An even distribution between a few species, producing a high value for H(S), may occur in estuarine and marginal marine environments (Alve and Murray, 1995a).

In the present context, the most important difference between Restronguet Creek and the control estuaries is the absence of the agglutinating species *M. fusca*, *J. macrescens* and *T. inflata* from the Restronguet Creek samples, leading to low diversity assemblages throughout, but particularly in the upper Creek which has similar salinity and temperature ranges to that recorded for the control estuaries (Chapter Four, Section 4.3).

5.4 Species distribution and dominance

5.4.1 Introduction

The term 'species dominance' has been used here when there is a difference of 5% or more between the most abundant species and the species next in abundance. Co-dominance is said to occur when abundances are closer than 5%. Particular species dominance of an assemblage may change with season and when these temporal spatial shifts occur the area is termed a 'transitional species zone'.

5.4.2 Distribution and dominance

i) Restronguet Creek

Haynesina germanica, *E. williamsoni* and, occasionally, *A. beccarii* formed major associations in Restronguet Creek. In the majority of examples, the autumn species distributions were characterised by the dominance of *E. williamsoni* which had the highest percentages during each year (Figure 5.10, a - e) varying between 12% and 100% (1992 - 1996). In autumn 1992, 1994 and 1995 (Figure 5.10, a, c and d) all stations were dominated by *E. williamsoni* with the exception of stations P10 (dominated in 1992 by *H. germanica*), and, TW27 and BY28 (1994) which were dominated by *A. beccarii*. In autumn 1993 a more variable species distribution was evident and single species dominance was randomly distributed (Figure 5.10b). *Haynesina germanica*, with an overall autumn distribution that varied between 1% and 77%, was generally second in abundance to *E. williamsoni* with the exception of stations TC6, TC8, TW27 and PI30 in 1993 which were dominanted by *H. germanica* (Figure 5.10b). Otherwise *H. germanica* co-dominated at certain stations with *E. williamsoni*, (Figure 5.10, a and e) and with *A. beccarii* (Figure 5.10b). In autumn 1993, *H. germanica* and *E. williamsoni* each show a decline in percentage proportions down the north side of the Creek between stations TC6 and CY16 which is in line with an increase in the proportions of *A. beccarii*, particularly at station CY16 (Figure 5.10b). Furthermore, the percentage difference between the three species at CY16 is marginal.

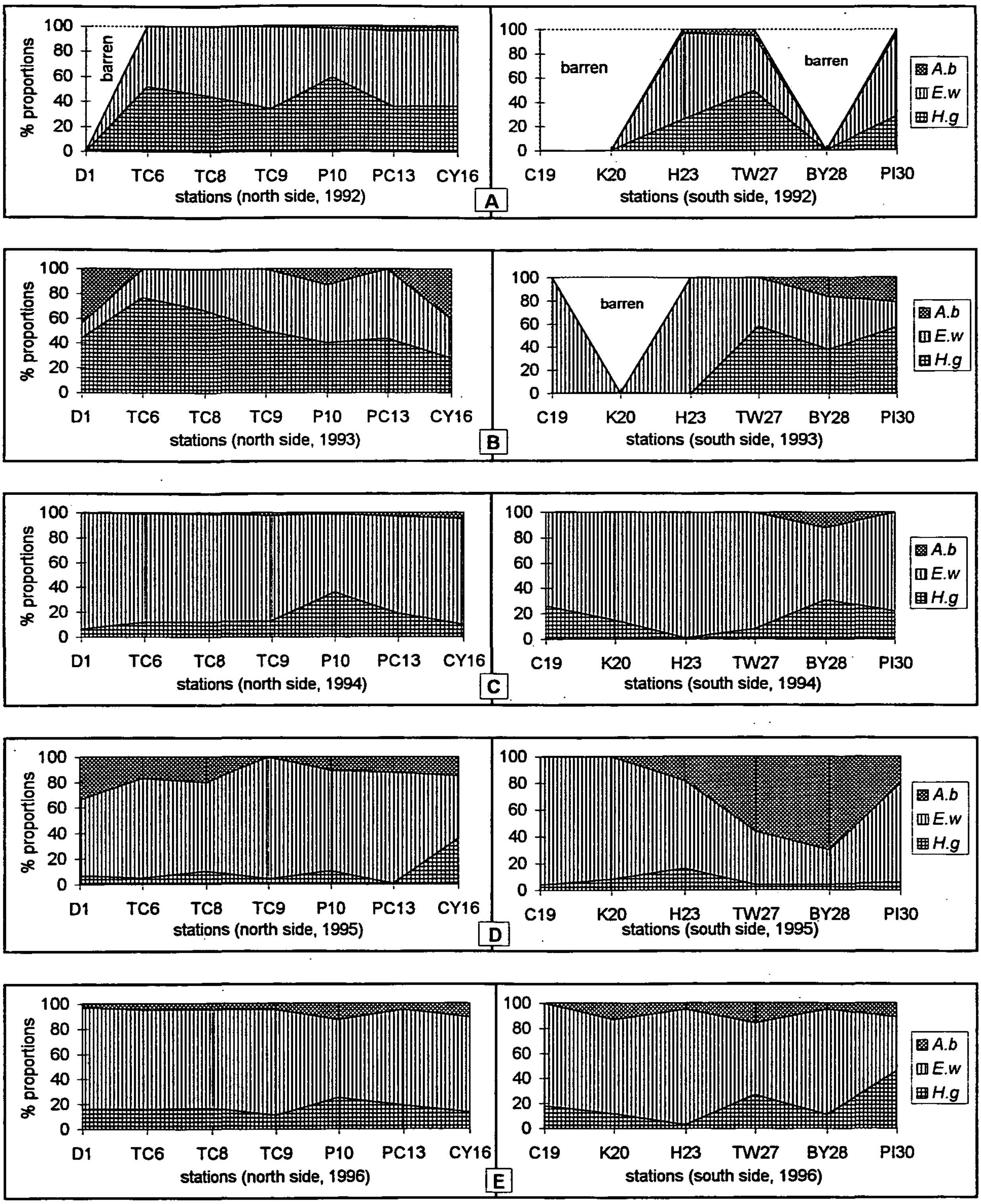


Figure 5.10: Autumn species distribution, Restronguet Creek. a) 1992, b) 1993,c) 1994, d) 1995 and e) 1996. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni* and *H.g.* = *H. germanica*.

On the south side of the Creek the proportions of *E. williamsoni* are reduced in line with an increase of the other two species. *Ammonia beccarii* was a subordinate species with a range of 0% - 70%. The zero scores were the most frequent in the early stages of sampling (1992 - 1994 inclusive) particularly above stations P10 and TW27 (Figure 5.10, a, b and c). In autumn 1995 and thereafter, *A. beccarii* appears more frequently and instances of its assemblage dominance appear after this time (TW27 and BY28 in 1995).

Elphidium williamsoni had an overall range in the winter (1993 - 1996) of between 0% and 100%. The lowest values were recorded in the years 1993 and 1994, when *E. williamsoni* was the dominant species at only one station, TC9 in 1993 and at stations CY16 and PI30 in 1994 (Figure 5.11, a and b). The other stations in 1993 and 1994 were dominated by *H.germanica*. In 1995 and 1996, *E. williamsoni* increased in it's proportions and the highest values were, in the majority of cases, recorded during these years. The overall range for *H. germanica* varied between 2% and 82% with the lower values being more common in 1995 and 1996. The proportions of *H. germanica* (3% - 30%) sharply declined in 1996 relative to the years 1993,1994 and 1995 (Figure 5.11, a, b and c). Furthermore, in 1995 *H. germanica* dominated the assemblages at stations P10 and CY16 with all other stations being dominated by *E. williamsoni*. *Ammonia beccarii* was commonly a subordinate species in the winter and had an overall range of between 0% and 100% and was absent at many stations in 1993, 1994 and 1995. In winter 1996, however, *A. beccarii* dominated the assemblages at stations P10, PC13 and K20 and co-dominated at TW27, BY28 and CY16 with *E. williamsoni*. At stations TC6 and TC9 in 1996 (Figure 5.11d), the proportions between the three species *E. williamsoni* (39%, 41% respectively), *A. beccarii* (33%, 33% respectively), *H. germanica* (28%, 26%

respectively) were similar and as a result the Shannon-Weiner Information Function values [H(S)] of 1.09 and 1.08 respectively, were much higher than elsewhere.

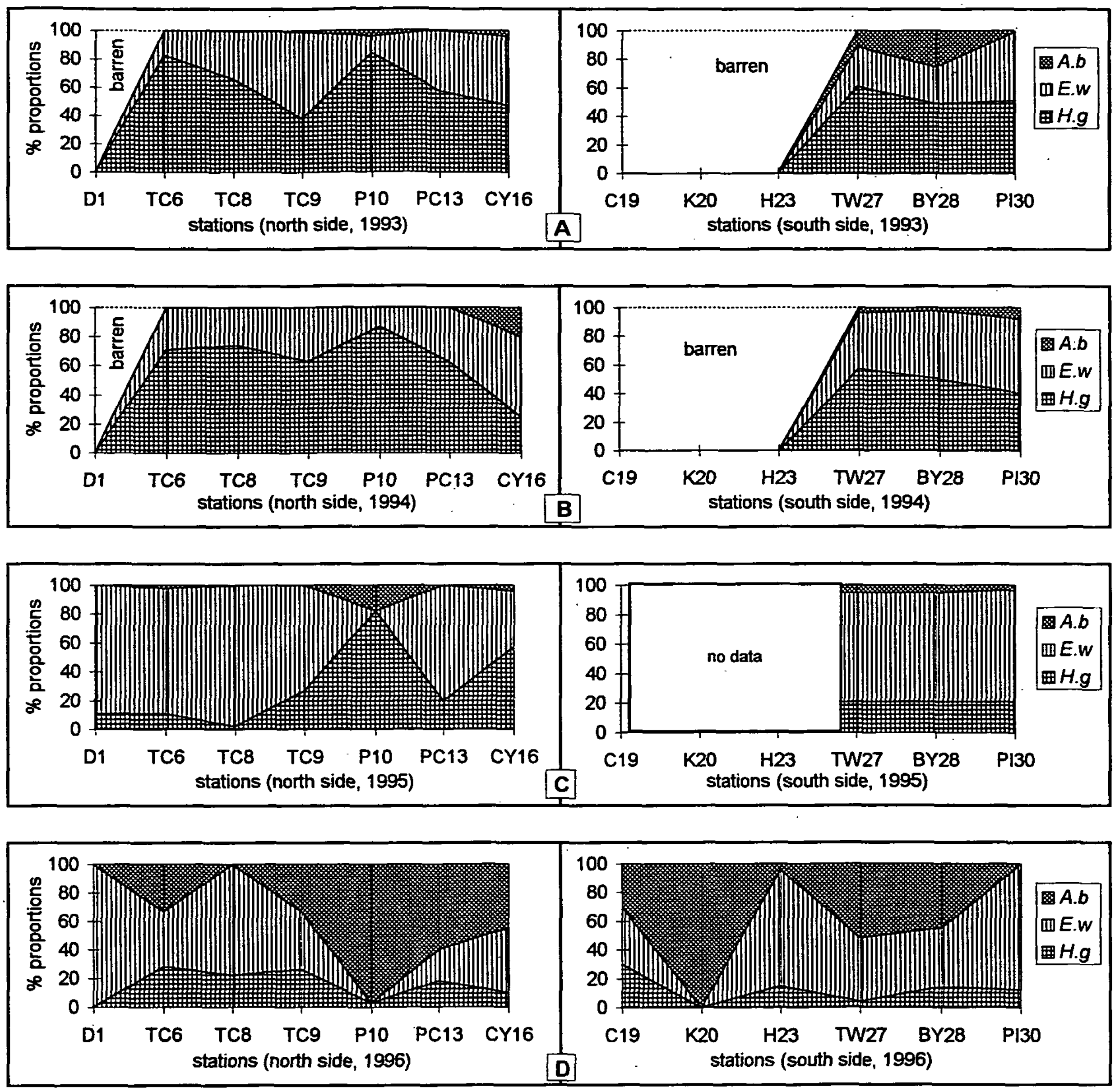


Figure 5.11: Winter species distribution, Restronguet Creek. a) 1993, b) 1994, c) 1995 and d) 1996. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni* and *H.g.* = *H. germanica.*

Haynesina germanica had an overall spring range of between 44% and 100%, the higher values being particularly frequent in 1993 and 1994. The assemblages throughout Restronguet Creek in 1993 and 1994 were, in the majority of cases, dominated by *H. germanica* (Figure 5.12, a and b). In spring 1995

(Figure 5.12c), however, the proportions of *H. germanica* were reduced relative to the previous year particularly at stations TC6, TC8, TC9, and at stations BY28 and PI30 on the south side. Despite this reduction, this species still dominated the assemblages at all stations with the exception of TC6 and TC9 which were dominated by *E. williamsoni*.

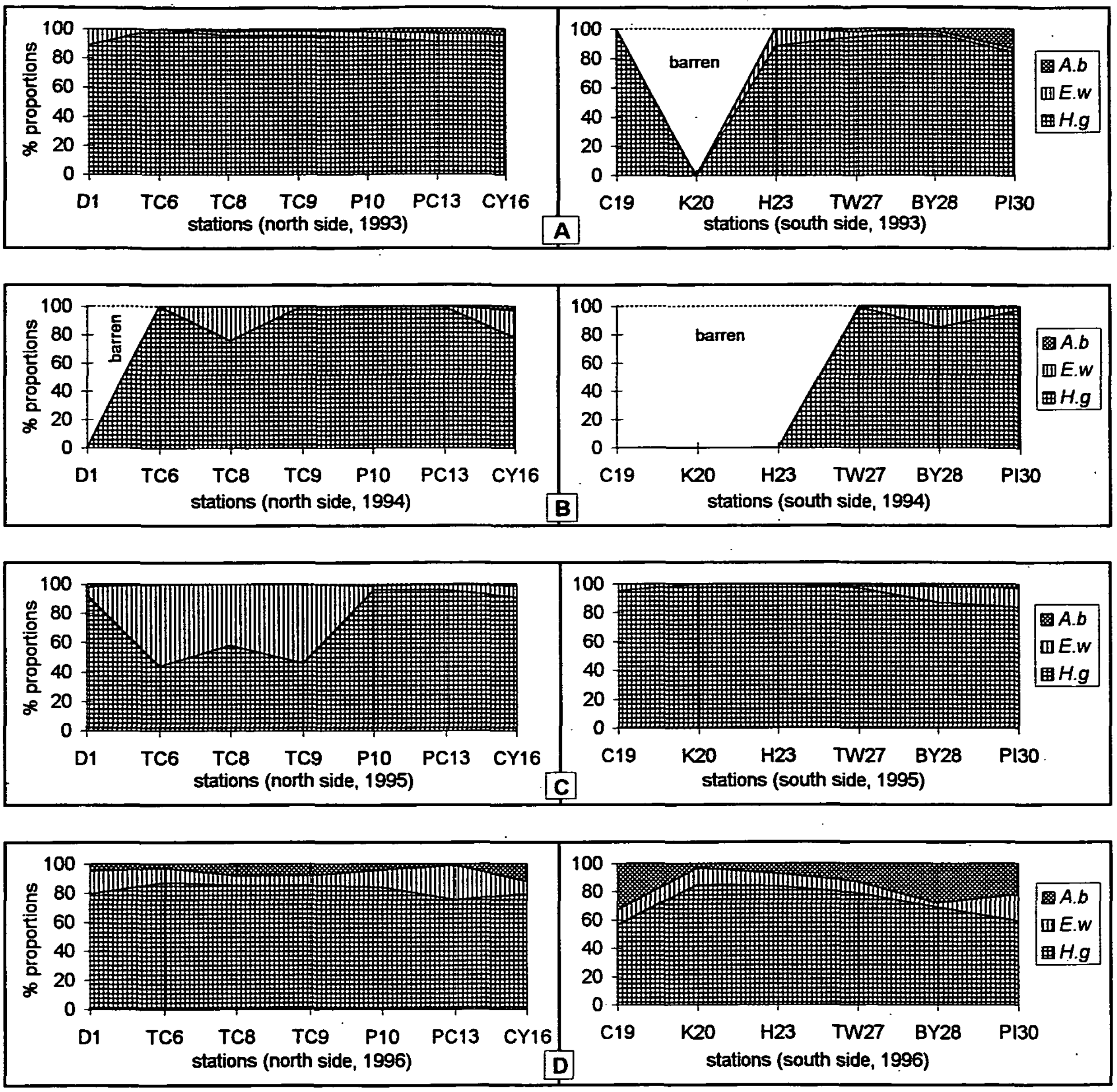


Figure 5.12: Spring species distribution, Restronguet Creek. a) 1993, b) 1994, c) 1995 and d) 1996. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni* and *H.g.* = *H. germanica*.

In 1996 all stations were dominated by *H. germanica* (Figure 5.12d). *Elphidium williamsoni* was a subordinate species in 1993 and 1994 and varied between 0% and 24% but increased in it's proportions in 1995 (3% - 56%) and to a lesser extent in 1996 (3% - 24%). *Ammonia beccarii* was also a subordinate species in 1993 and 1994 with a range for the two years of between 0% and 13%. *Ammonia beccarii* varied between 0% and 3% in 1995 (Figure 5.12c) and was generally absent but in 1996 increased in it's proportions and varied between 1% and 33% (Figure 5.12d). There were no instances of co-dominance between species during the spring of each year.

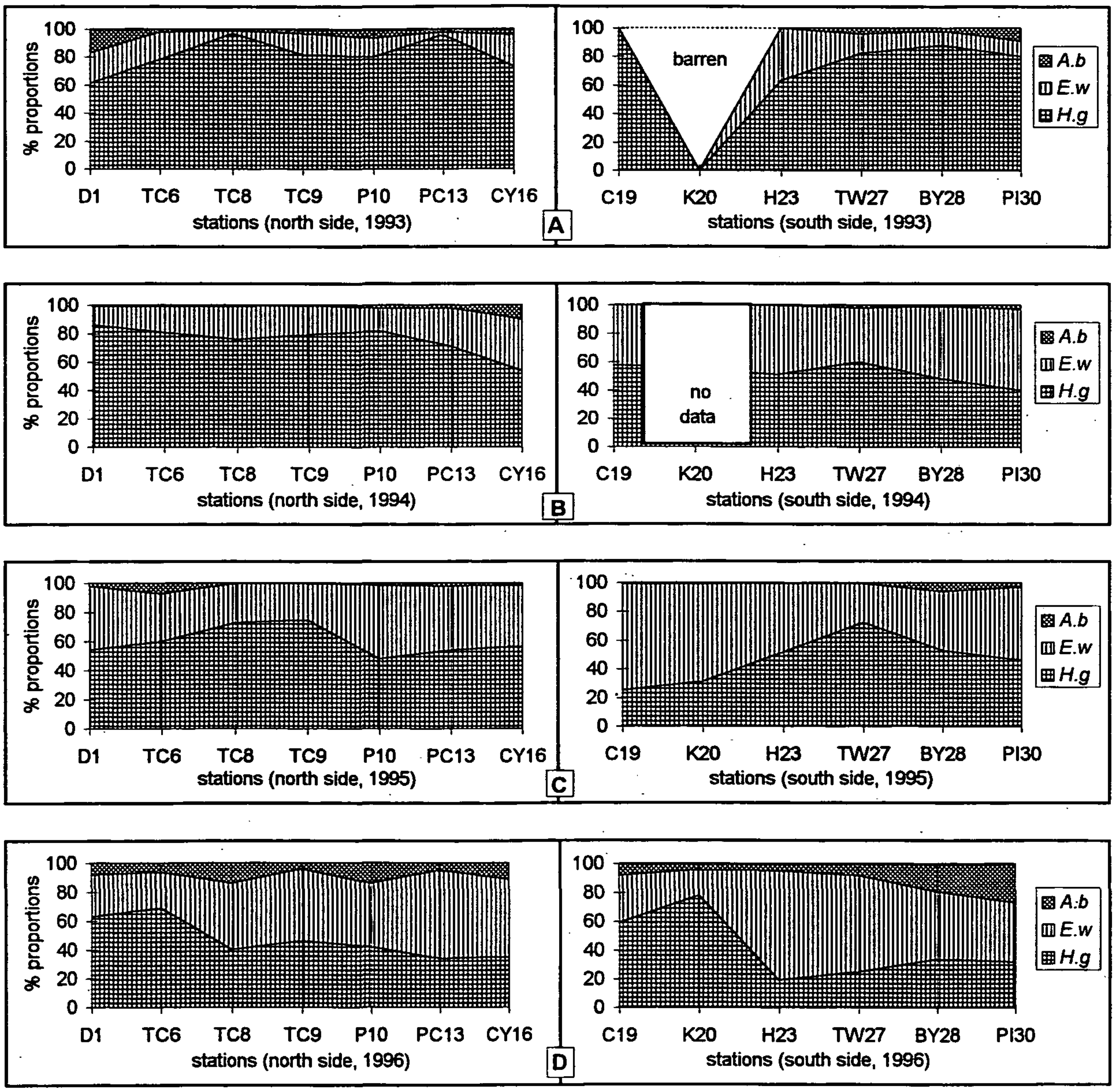


Figure 5.13: Summer species distribution, Restronguet Creek. a) 1993, b) 1994, c) 1995 and d) 1996. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni* and *H.g.* = *H. germanica*.

The summer assemblages were generally characterised by *H. germanica* associations. *Haynesina germanica* had an overall summer range between 19% and 100% with the highest values more frequently recorded in 1993 (Figure 5.13a) and to a lesser extent in 1994 (Figure 5.13b) relative to 1995 and 1996. In 1993 and 1994 all the summer assemblages were dominated by *H. germanica*, with the exception of stations H23 and BY28 (1994) which were co-dominated by *E. williamsoni* and *H. germanica*. In 1995 stations K20 and C19 were dominated by *E. williamsoni* (Figure 5.13c) and in 1996 *E. williamsoni* dominated or co-dominated with *H. germanica* at each assemblage in the mid - low Creek stations (Figure 5.13d). *Elphidium williamsoni* had an overall summer range between 1993 and 1996 of 2% - 75% and for *A. beccarii* the range was 0% - 27%. Between 1993 and 1995 *A. beccarii* was a subordinate species and was often absent. In 1996 it was present at all stations with a maximum value of 27%.

In summary, therefore, spatial species distribution and dominance have been variable in Restronguet Creek with *H. germanica* being a more important species in the spring and summer and *E. williamsoni* in the autumn and winter. *Ammonia beccarii*, though often numerous, was normally less abundant than these species. The earlier (pre - 1995) assemblage dominance of *H. germanica* in the winter ceased after this year and was replaced by the exclusive dominance of *E. williamsoni*. *Elphidium williamsoni* has shown increasingly higher percentage proportions in the spring and summer in the later stages of the sampling programme (post - 1995) and in 1996, for example, this species dominated, or co-dominated, the assemblages at 9 out of 13 stations in the mid - to low Creek area. Overall, *A. beccarii* has increased it's proportions since autumn 1992, particularly during the autumn of 1995 and winter of 1996. Evidently, the three species present do not have a spatially fixed distribution and the two major species, *H. germanica* and *E. williamsoni* are also becoming less temporally (seasonally) predictable with the post - 1994 data appearing to mark a change in species distribution and dominance.

ii) The Erme Estuary

Elphidium williamsoni, *M. fusca* and to a lesser extent, *H. germanica* form major assemblage associations in the Erme Estuary but which are controlled by season and spatial distribution. The annual ranges of the three major species are: *H. germanica* 0% -72%, *E. williamsoni*, 0% - 92% and *M. fusca* 0% - 100%.

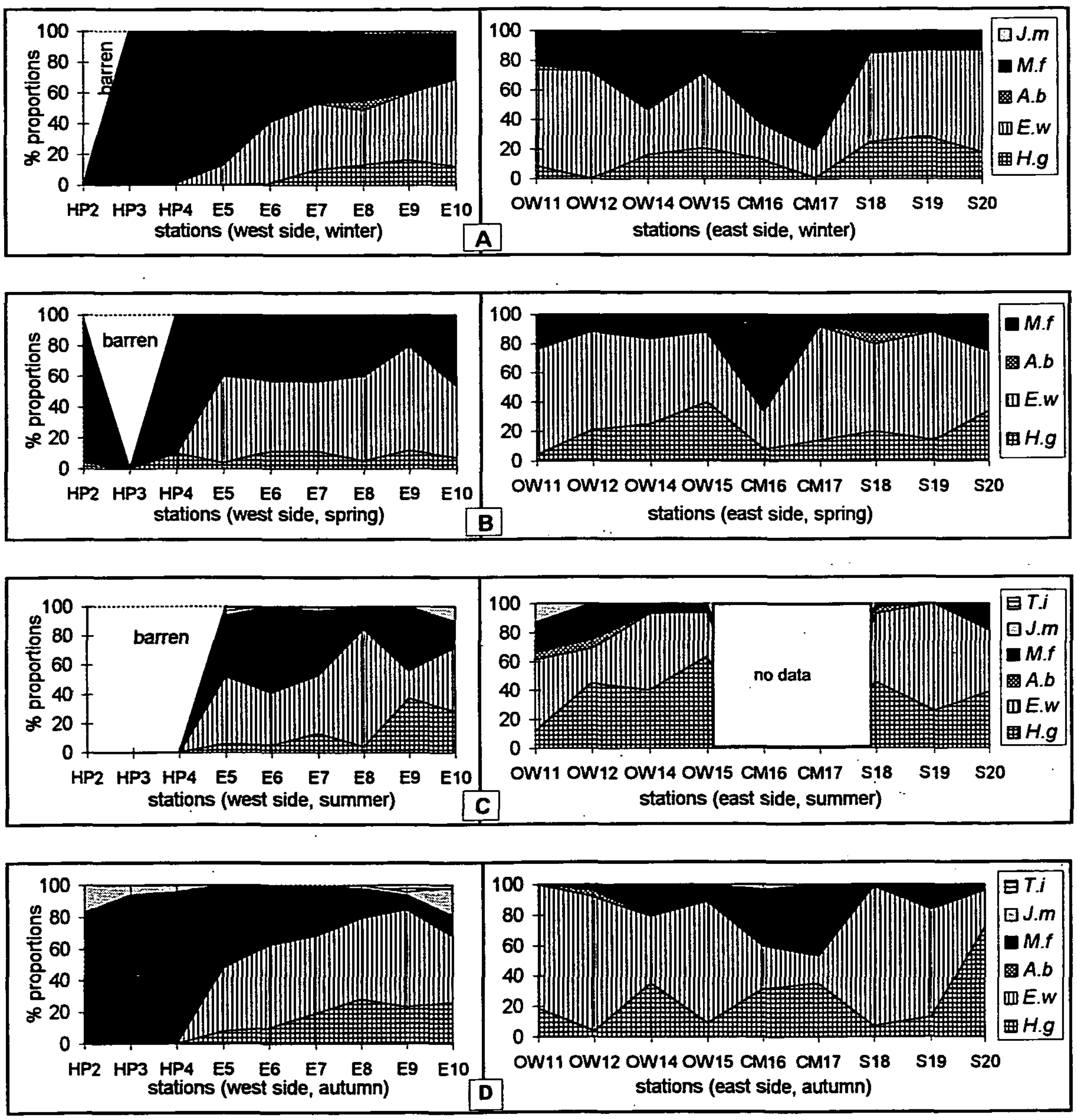


Figure 5.14: Species distribution, Erme Estuary. a) winter, b) spring, c) summer and d) autumn. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni*, *H.g.* = *H. germanica*, *M.f.* = *M. fusca*, *T.i.* = *T. inflata* and *J.m.* = *J. macrescens*.

The upper estuary stations HP2, HP3 and HP4, are characterised by the monospecific presence of *M. fusca* for all seasons (Figure 5.14, a - d). In the winter, assemblage domination by *M. fusca* spatially expands into the mid - estuary at stations E5, E6 and E8, and co-dominates with *E. williamsoni* at stations E7 and E9. In the spring, the distribution of *M. fusca* is more restricted. On the east side *M. fusca* dominated only those assemblages at the Clyng Mill Creek stations, OW14 (winter only), CM16 (autumn, winter and spring) and CM17 (autumn and winter). Otherwise, *M. fusca* co-dominates with *E. williamsoni* at certain stations in the mid- and low estuary in the spring and summer (Figure 5.14, b and c). The distribution of *M. fusca* declines down estuary on the west side and shows a near linear trend winter and autumn 1993 (Figure 5.14a). A less predictable trend is shown by the east side of the estuary. In the majority of cases the mid - low estuary stations are characterised by an *E. williamsoni* association, particularly in the autumn (Figure 5.14, b and d). Stations OW11 and OW12 are dominated all year by *E. williamsoni* except for summer when the assemblage at OW12 is dominated by *H. germanica*. The proportions of *H. germanica* increase in the summer, and it appears at all stations except those in the upper estuary. *Haynesina germanica* dominated the assemblages at stations OW12 and OW15 in the summer and at station S20 in the autumn. *Elphidium williamsoni* and *H. germanica* co-dominated the assemblages at stations S18 and S20 in the summer. The other species, *A. beccarii* (0% - 7%), *Jadammina macrescens* (0% - 2%) and *Trochammina inflata* (0% - 2%) had low proportions and did not appear at all stations.

In summary, *M. fusca* and *E. williamsoni* together formed the major assemblage associations and showed spatial changes in their proportions and dominance during each season. The upper estuary stations HP2 - 4 and the creek station CM16, however, formed spatially distinct areas in faunal dominance and were dominated by *M. fusca* all year. Seasonally, *M. fusca* is a more important species in the winter and extends its spatial domination further down estuary, forming a transitional species zones (Stubbles, 1995). *Haynesina germanica* was a minor species except in the summer and to a lesser extent in the autumn. Overall, however, *E. williamsoni* was the most abundant and widespread species. The percentage proportions of the minor species, *A. beccarii*, *T. inflata* and *J. macrescens* increased down estuary.

***iii*) The Fowey Estuary**

Haynesina germanica, *E. williamsoni* and to a lesser extent, *M. fusca* form major associations in the Fowey Estuary which are seasonally and spatially controlled. The annual range for each species is the same, 0% - 100%. Overall, *H. germanica* had the highest percentage proportions in the spring and summer and dominated the assemblages at all stations (Figure 5.15, a and b) with the exception of stations StW2, LPO3 and RC4 which were dominated by *M. fusca* in the spring but not in the summer. The subsidary creek stations PM7 and PPH11 are dominated by *H. germanica* all year (except for autumn at station PM7) where salinity is high relative to Lerryn Creek (stations LPO3 and RC4). For the other seasons, autumn and winter, the upper estuary and subsidary creek stations StW1 (winter only), LPO3 and RC4 were dominated by *M. fusca*. These assemblages in the winter were monospecific. *Miliammina fusca* is a minor species on both sides of the lower estuary (Figure 5.15, a - d). *Elphidium williamsoni* dominated the assemblages in the main channel in the autumn and to a lesser extent in the winter (Figure 5.15, c and d) and was the only species present at station G14 in the winter. Species distribution on both sides of the estuary is, in general, smooth except in winter which shows an erratic profile between the proportions of *H. germanica*, *E. williamsoni* and *A. beccarii*. *Ammonia beccarii,* *J. macrescens* and *T. inflata* were subordinate species, the latter two being largely rare. In the autumn, *J. macrescens* comprised 20% of the stained assemblage at station LPO3.

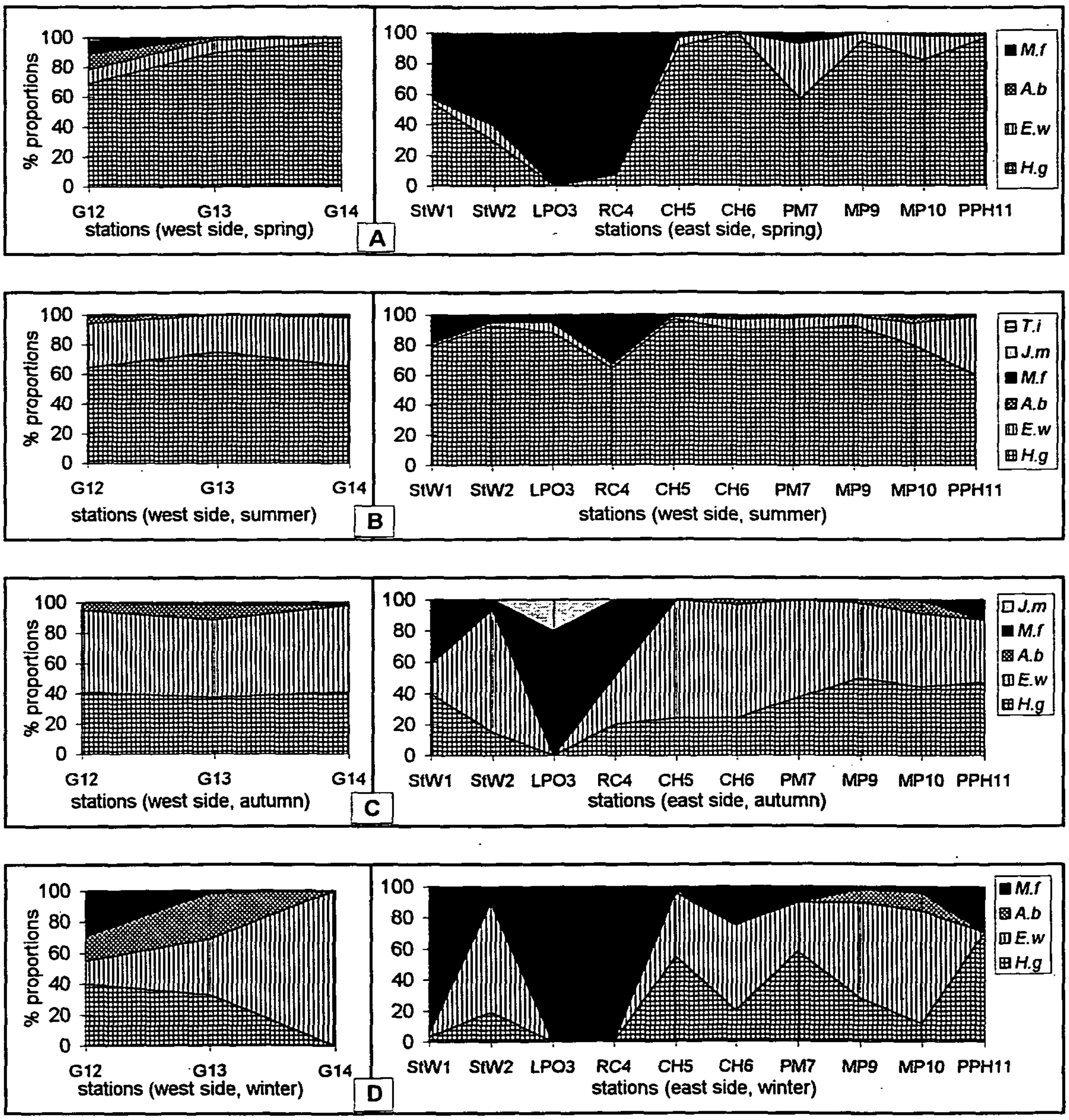


Figure 5.15: Species distribution, Fowey Estuary. a) spring, b) summer, c) autumn and d) winter. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni*, *H.g.* = *H. germanica*, *M.f.* = *M. fusca*, *T.i.* = *T. inflata* and *J.m.* = *J. macrescens*.

In summary, *H. germanica* was the most abundant and widespread species in the main channel of the Fowey Estuary particularly in the spring and summer, but less so in the subsidiary Lerryn Creek. In the autumn and winter the proportions of *E. williamsoni* increased with more instances of it's assemblage dominance. The seasonal dominance by *M. fusca* at the upper estuary stations StW1 and StW2, and, creek stations LPO3 and RC4 represents a transitional zone (Figure 5.15, a, c and d) in the spring and winter, and with respect to LPO3 in the autumn also. It would appear that temporally, the *M. fusca* associations were restricted to the cooler and lower salinity water conditions of the upper estuary and Lerryn Creek. In the winter *A. beccarii* had the highest proportions but remained a minor species. There were rare occurrences of *J. macrescens* and *T. inflata*.

***iv*) The Avon Estuary**

The Avon Estuary is characterised by two major species associations; *E. williamsoni* and *M. fusca* with *H. germanica* as a common additional species (Murray, 1991). The annual range for each species varied as follows: *H. germanica*, 0% - 30%, *E. williamsoni*, 0% - 93% and *M. fusca*, 0 - 100%. The highest proportions of *M. fusca* were present at the upper estuary stations A1 and A2 during all seasons and at A9 in the summer, winter and spring (Figure 5.16, a - d). In the spring, *M. fusca* dominated the assemblages at all stations except A3, A8 and A10 (Figure 5.16d). The proportions of *M. fusca* generally decreased down estuary in line with an increase in calcareous taxa (Figure 5.16, a and c). *Elphidium williamsoni* was overall the dominant species in the remainder of the estuary, particularly in the winter and autumn on the east side. The species distribution at station A3 in the summer (Figure 5.16a) had relatively even proportions between *M. fusca* (28%), *E. williamsoni* (28%), *A. beccarii* (22%) and *H. germanica* (21%) and, hence the highest values of the

Shannon-Weiner Information Function [H(S)] were recorded here (1.38). *Haynesina germanica* was not present at all stations but it's proportions increased in the summer relative to the other seasons and the maximum values were recorded on the west side. Throughout the estuary *A. beccarii* had low - moderate proportions (0% - 53%) which were highest in the autumn and dominated the assemblage at station A3. *Jadammina macrescens* (0% - 6%) and *T. inflata* (0% - 1%) were rare. The distribution of *E. williamsoni* and *M. fusca*, particularly on the east side, showed a near linear trend (Figure 5.15a), with an inverse proportional relationship to each other.

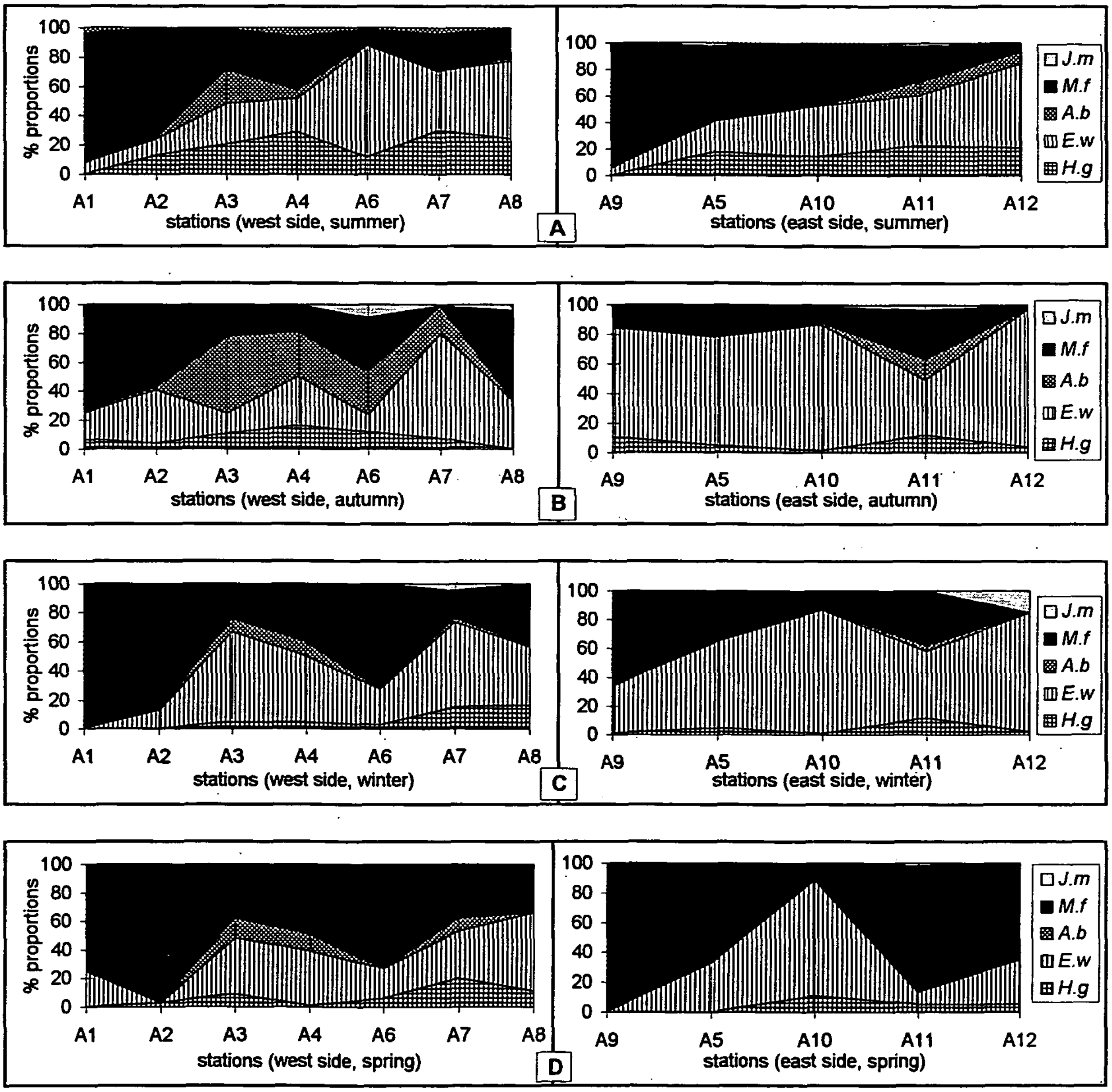


Figure 5.16: Species distribution, Avon Estuary. a) summer, b) autumn, c) winter and d) spring. Abbreviations: *A.b.* = *A. beccarii*, *E.w.* = *E. williamsoni*, *H.g.* = *H. germanica*, *M.f.* = *M. fusca*, *T.i.* = *T. inflata* and *J.m.* = *J. macrescens*.

In summary, the assemblages of the upper estuary stations A1 and A2 were dominated by *M. fusca* with *E. williamsoni* second in abundance for all seasons. The assemblage at the other upper estuary station, A9, was dominated by *M. fusca* in the summer, winter and spring, but in the autumn was dominated by *E. williamsoni* with *M. fusca* second in abundance. During the spring, *M. fusca* dominated the assemblages at the majority of stations in the mid - estuary which formed a transitional species zone. *Elphidium williamsoni* had higher proportions in the mid - low estuary in the winter, autumn and summer. *Haynesina germanica* had higher proportions in the summer but remained a subordinate species. The proportions of *A. beccarii* increased in the autumn but overall, as with *J. macrescens* and *T. inflata*, was a subordinate species. Evidently, species distribution was not spatially or temporally fixed, particularly in the area of the low and mid - estuary.

5.5 Variation in species distribution between sample locations

i) Restronguet Creek and the Erme Estuary

The MDS plots (multi-dimensional scaling) show similarities/dissimilarities between the Restronguet Creek data points and those of the Erme Estuary (Figure 5.17, a - d). Overall, the Erme and Restronguet Creek data points differentiate into two groups (each enclosed by a wide dashed line) with stations of the latter location arranged to form the tightest grouping, particularly for winter (Figure 5.17a). This spatial closeness reflects strong similarity in species assemblage composition between the Creek sample stations. The Restronguet Creek data has a wider dispersal in the autumn within which four subsidiary groups can be defined (each enclosed by a fine dashed line). The box enclosed stations (TC6 etc.) represent tight clusters which plot on the same point, having closely similar species proportions.

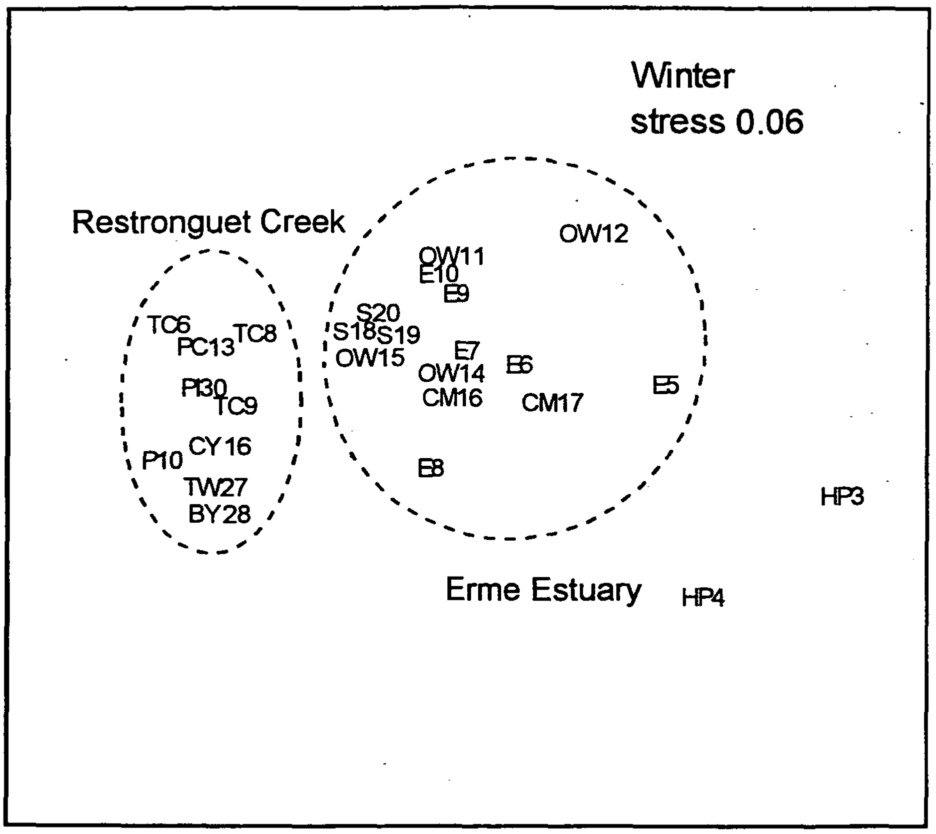


Figure 5.17a: Comparisons in species distribution and dominance between Restronguet Creek and the Erme Estuary, winter.

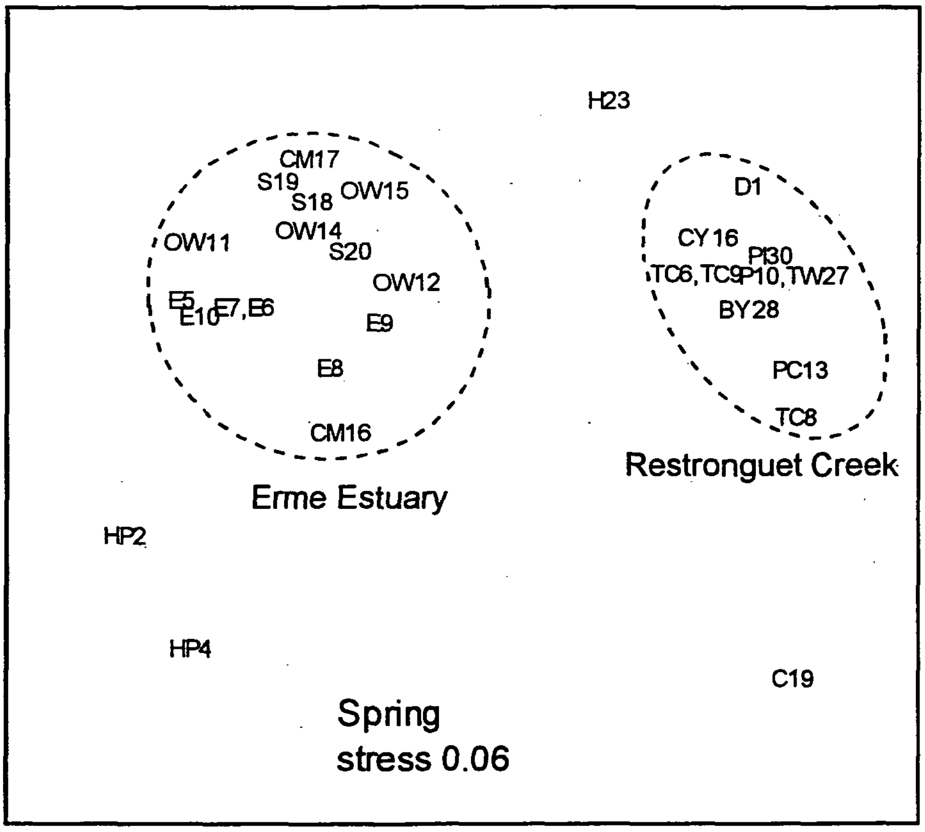


Figure 5.17b: Comparisons in species distribution and dominance between, Restronguet Creek and the Erme Estuary, spring.

The wider dispersal shown by the Erme data reflects greater dissimilarity in species composition between the respective subgroups and the number of species present at each station (Figure 5.17d). This is particularly evident with respect to the Erme stations HP2, HP3, HP4 which are distinct to the main Erme group, and reflect the higher proportions of *M. fusca* at these stations, in most cases being monospecific (Section 5.4.2. *ii*). The Restronguet Creek station C19 is routinely different from the other Creek stations in the spring and summer (Figure 5.17, b and c) and with H23 in the autumn which reflects the monospecific appearance of *H. germanica* at these stations. The relatively reduced spatial separation shown between the two locations in the summer (notably between stations H23 and S19) is due to the lower proportions of *M. fusca* and higher proportions of *H. germanica* (Figure 5.17c) in the Erme Estuary. The species distribution patterns in the Erme Estuary resembles that of Restronguet Creek during this season.

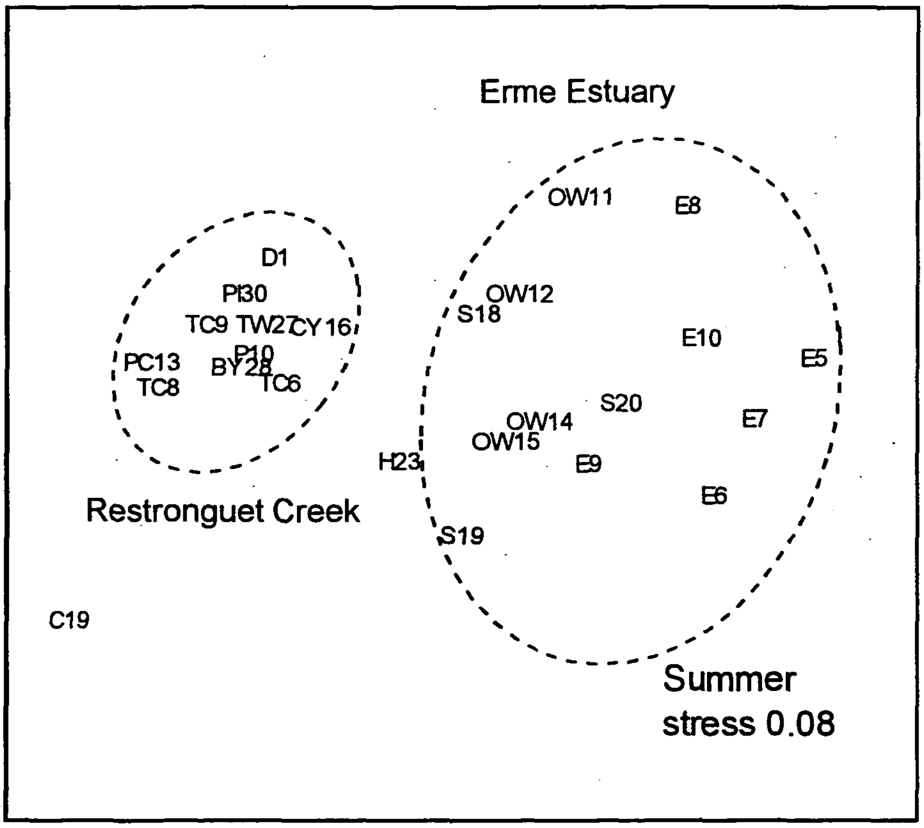


Figure 5.17c: Comparisons in species distribution and dominance between Restronguet Creek and the Erme Estuary, summer.

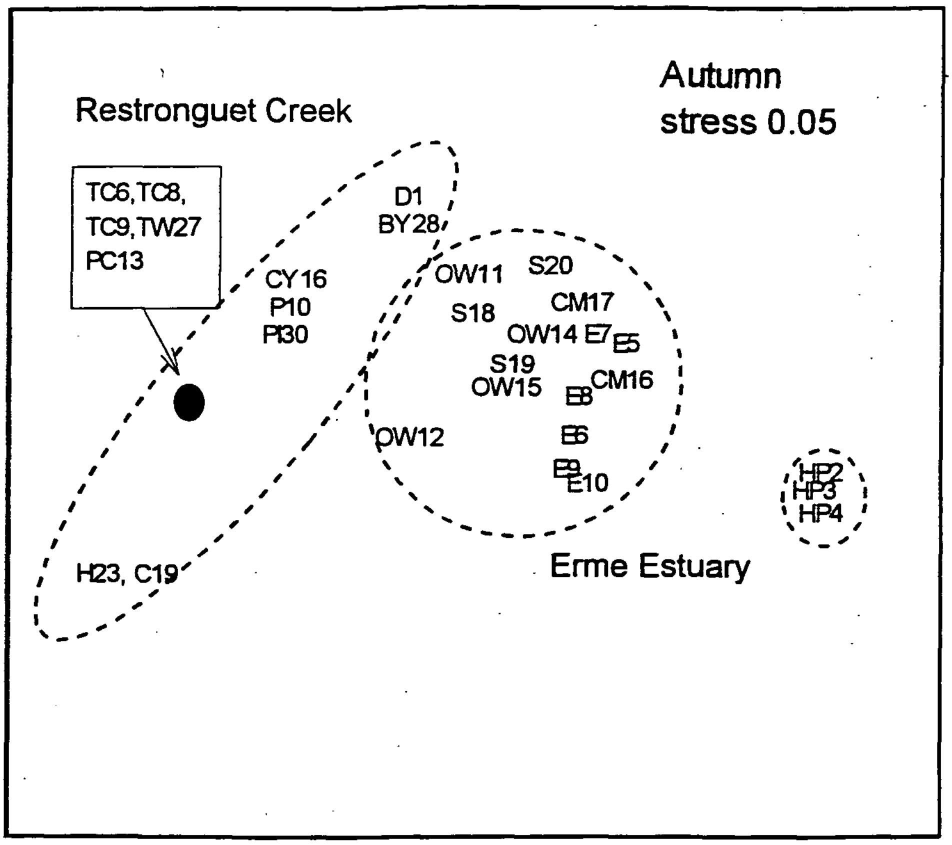


Figure 5.17d: Comparisons in species distribution and dominance between Restronguet Creek and the Erme Estuary, autumn.

***ii)* Restronguet Creek and the Fowey Estuary**

Each of the Fowey Estuary and Restronguet Creek seasonal MDS plots show distinctive spatial separation between the two locations (Figure 5.18, a - c). Spatial distinctiveness is more pronounced for the spring and autumn (Figure 5.18, a and b). There is a narrower spatial separation shown for the winter and hence, greater similarity between the two locations (Figure 5.18d). Similarity between the two locations is greatest in the summer and the majority of stations, with the exception of stations StW1 and RC4, form one tight cluster upon the same point. As these points could not be separated the plot is not reproduced. For the summer, therefore, Restronguet Creek and the Fowey Estuary are closely similar having assemblages dominated by *H. germanica*, in the majority of examples. Stations StW1 and RC4, also show a dissimilarity relative to LPO3 (relative to the main Fowey group) for winter. This is also the case for spring when stations LPO3 and RC4 are distinctly separated from the main Fowey group. This is due in each case to assemblage dominance by *M. fusca* at these stations (Figure 5.18, a and c).

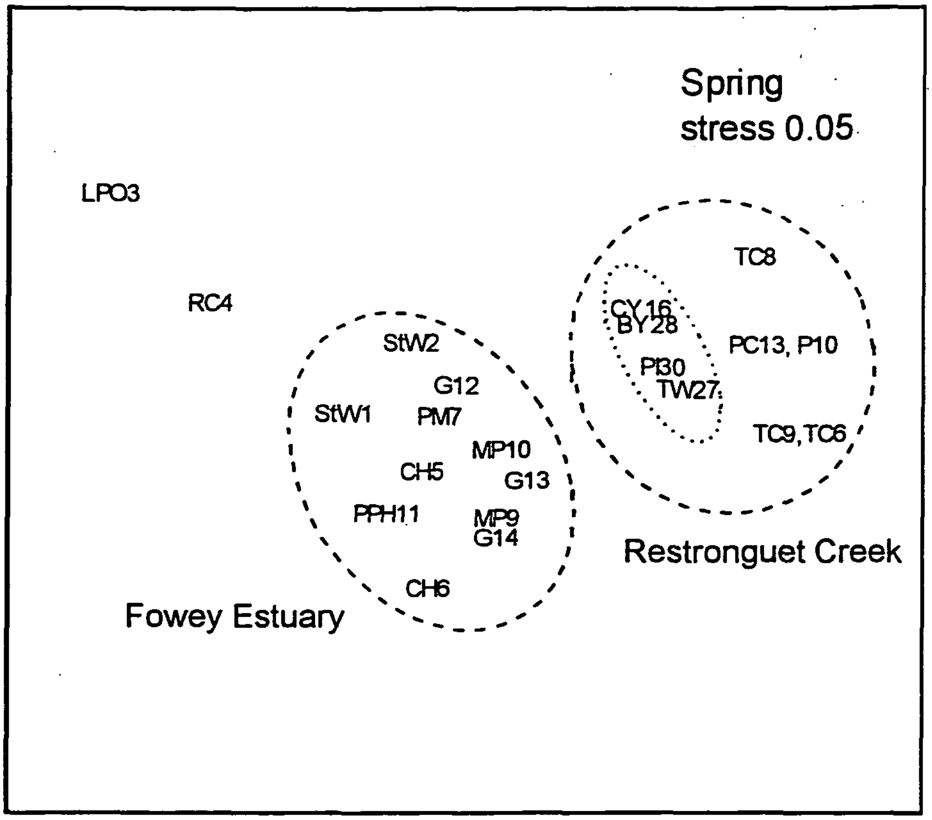


Figure 5.18a: Comparisons in species distribution and dominance between Restronguet Creek and the Fowey Estuary, spring.

For the winter (Figure 5.18c) compositional variation between the stations is greatest, in particular StW1 and PPH11 which are spatially separated from the main Fowey group. Station PPH11 is distinctly dissimilar, being dominated by *H. germanica*. Station G14 is closely associated with the lower end of the Restronguet Creek group because the assemblage comprises similarly higher proportions of *E. williamsoni*. Of the Restronguet Creek stations, P10 is spatially separated because the species assemblage is dominated by *H. germanica*, instead of *E. williamsoni* as elsewhere. Stations CH5, CH6 and G12 form differentiated subgroups within the main Fowey Estuary group (autumn and to a lesser extent winter) which reflects the absence of *M. fusca* at these stations.

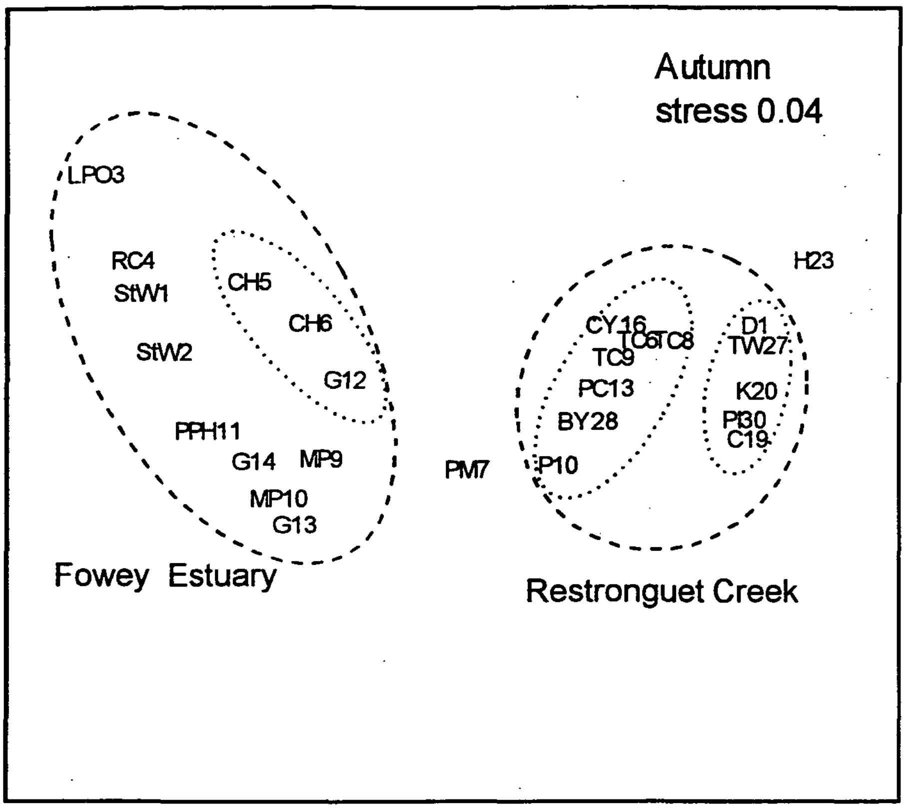


Figure 5.18b: Comparisons in species distribution and dominance between Restronguet Creek and the Fowey Estuary, autumn.

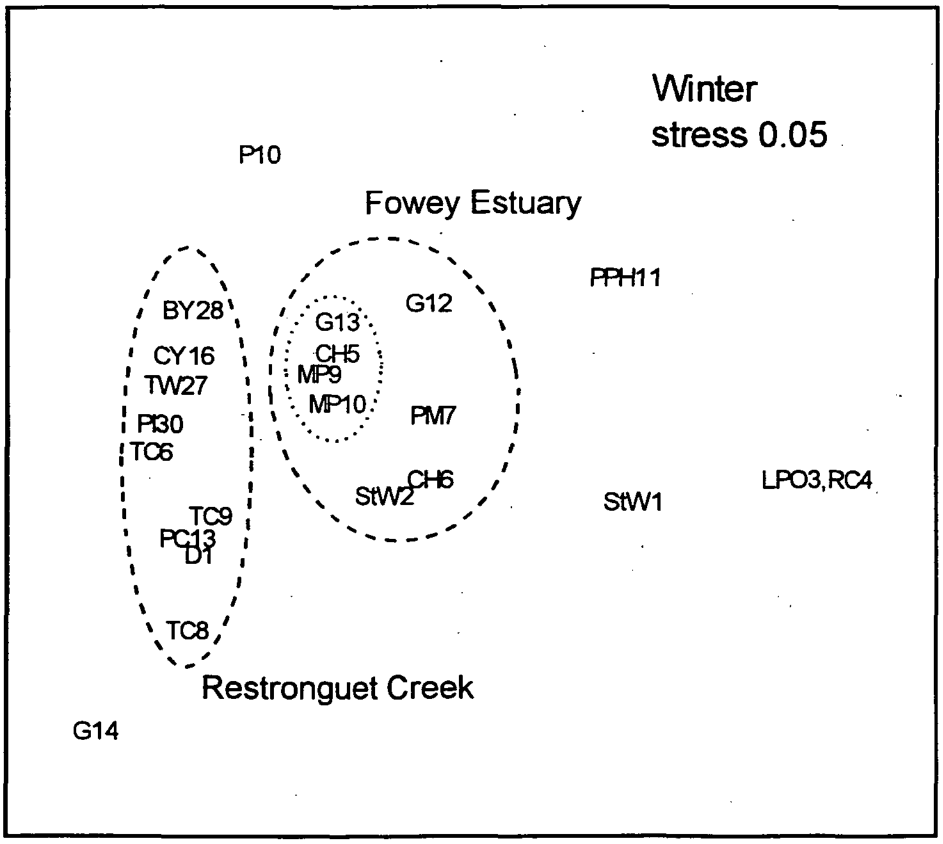


Figure 5.18c: Comparisons in species distribution and dominance between Restronguet Creek and the Fowey Estuary, winter.

Similarly, certain stations within the Restronguet Creek group are separated into subgroups (Figure 5.18b) which reflects the absence/presence of *A. beccarii.* Station PM7 is spatially associated with both the Restronguet Creek and Fowey Estuary groups and has a species composition that is closely similar to station P10.

***iii)* Restronguet Creek and the Avon Estuary**

The relative spatial arrangement of the Avon Estuary stations shows high dispersal, indicating high variation in species composition and the number of species present (Figure 5.19, a - d). There is least spatial separation shown between Restronguet Creek and the Avon Estuary in the winter (Figure 5.19c) and aside from station A7, the autumn shows the greatest spatial separation (Figure 5.19b). Only station A7 is in close proximity to the Restronguet Creek group which reflects a near all calcareous species composition, dominated by *E. williamsoni.* Stations A9 and A1 (summer), A2, A11 and A9 (spring), and, A1 and A2 (winter) lie outside the main Avon Estuary group and this is due to assemblage dominance by *M. fusca* on it's own, or with lower proportions of calcareous species. The Restronguet Creek data points are, however, routinely tightly grouped which indicates least variation in species composition between the Creek stations. The most notable exception to this is winter (Figure 5.19c) and stations D1, P10 and K20 are spatially separated from the main group which reflects greater compositional variation and a change in species dominance. Occasionally the distribution of the data points follows a linear pattern (Figure 5.19, a and c). This is particularly pronounced with respect to Restronguet Creek for summer and winter (1995 - 1996) and indicates changes in species composition down creek.

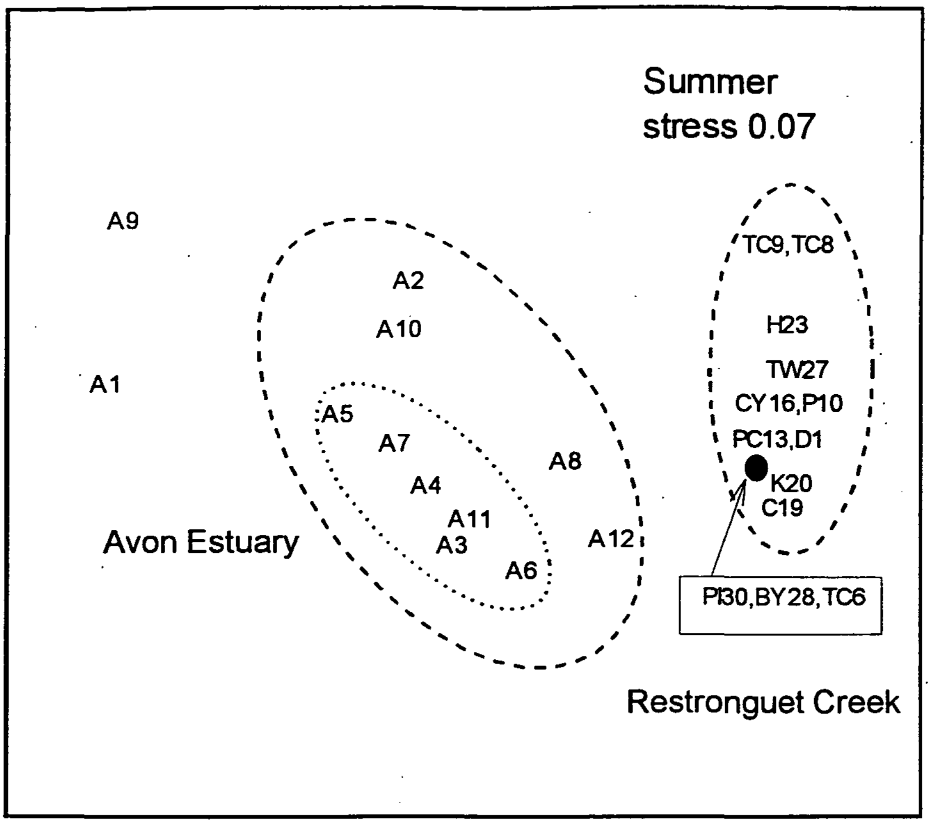


Figure 5.19a: Comparisons in species distribution and dominance between Restronguet Creek and the Avon Estuary, summer.

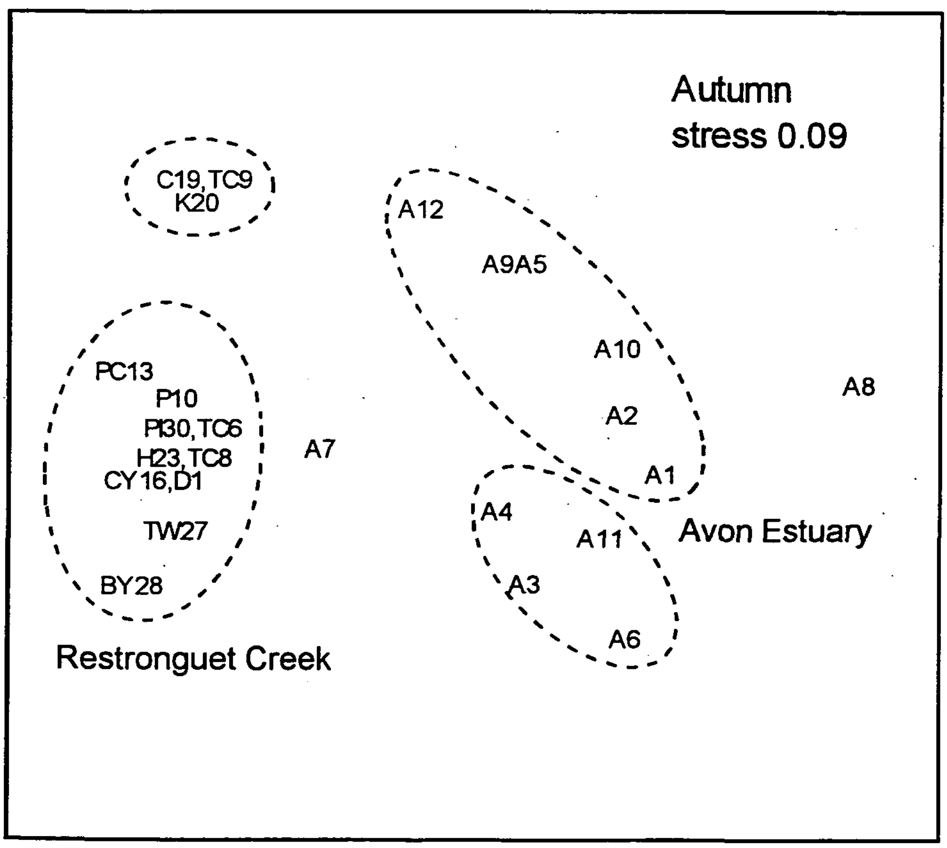


Figure 5.19b: Comparisons in species distribution and dominance between Restronguet Creek and the Avon Estuary, autumn.

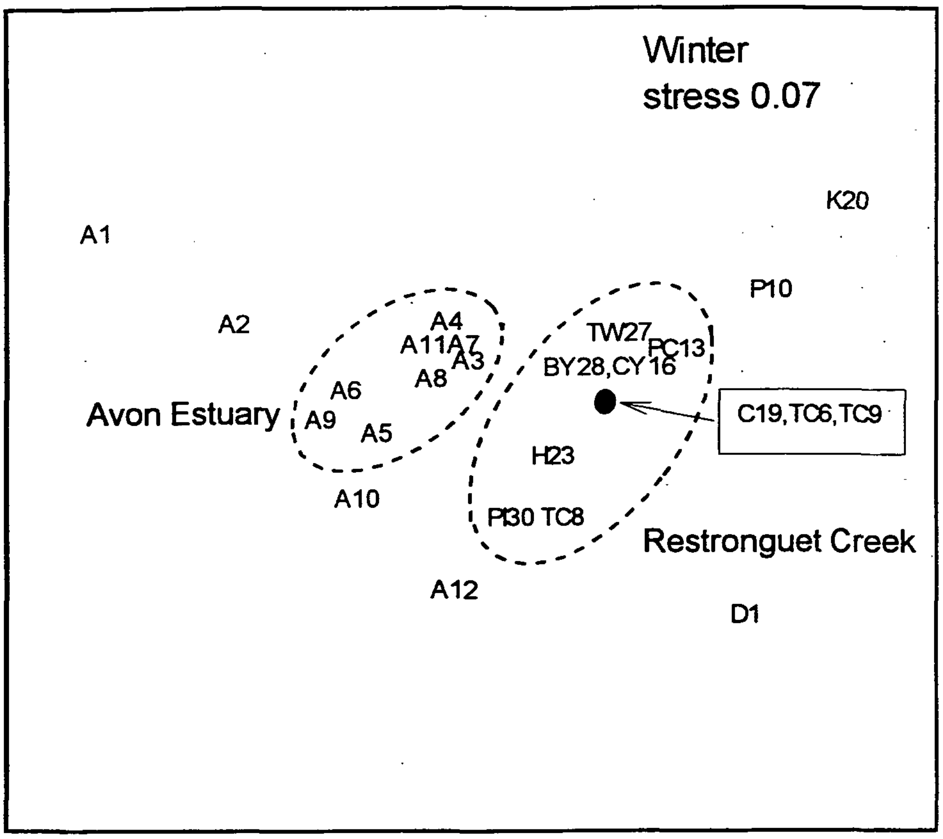


Figure 5.19c: Comparisons in species distribution and dominance between Restronguet Creek and the Avon Estuary, winter.

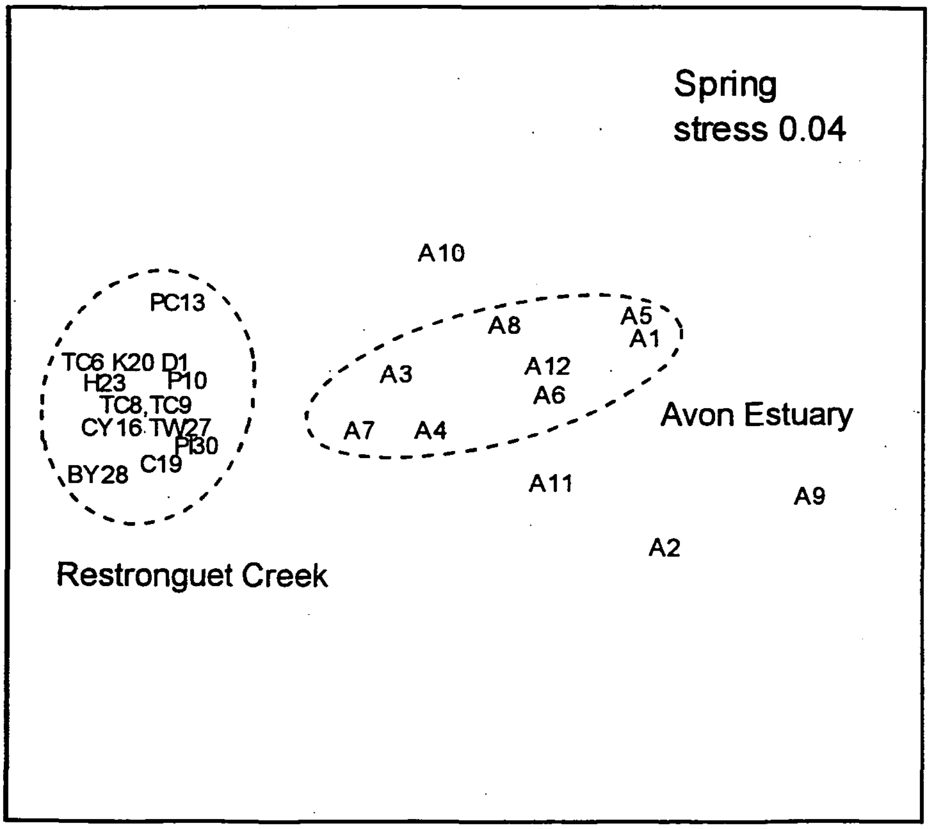


Figure 5.19d: Comparisons in species distribution and dominance between Restronguet Creek and the Avon Estuary, spring.

The Avon Estuary stations A3, A7, and A12 (winter) are spatially associated with certain Creek stations, in particular BY28 and CY16. This reflects greater similarity in species composition with lower proportions of *M. fusca* and assemblage dominance by *E. williamsoni* at stations A3, A7 and A12.

5.6 Statistical relationship between species distribution and other variables

***i*) Restronguet Creek**

As Table 5.3 shows, the correlation coefficients for species and salinity are all positive and generally significant with respect to *Ammonia beccarii* in the autumn, with the exception of 1993. For winter 1993 and 1994 the correlation between salinity and *A. beccarii* is similarly significant and for spring 1994 the relationship is strong (0.74). There is a strong and positive relationship shown between *E. williamsoni* and salinity for winter 1994 and 1995 (0.84), and for summer 1994 the relationship is significant (0.59). *Haynesina germanica* shows a significant positive correlation with salinity for winter and spring 1995 and in spring 1994 the relationship is strong (0.7). The relationship between *H. germanica* and salinity is negatively significant in summer 1996. Evidently, *A. beccarii* has a consistent preference for water with higher salinity in the lower Creek, whereas, the strength and type (+ or -) of association exhibited by *H. germanica* and, particularly, *E. williamsoni* varies with season and from year to year.

With the exception of *A. beccarii* (winter), there are no significant correlations between species and temperature for 1993 (Table 5.3). Significant relationships were shown by all three species and *H. germanica* in particular, is strongly related with temperature for summer 1996. For winter and summer 1994, *E. williamsoni* is the only species to show a significant and positive relationship with temperature (0.65 and

0.55, respectively).

Organic carbon (%) correlates significantly with *H. germanica* (0.62 and 0.58) and *E. williamsoni* (-0.64 and -0.55) for autumn 1994 and 1996 (Table 5.3). Otherwise, there are no significant correlations shown, the exceptions to this are *H. germanica*, which shows a negative, significant correlation for autumn 1995 and for winter 1996 the relationship is strong (-0.9. In the majority of examples the correlation between the C/N ratio and each species is not significant. *Ammonia beccarii* is only significantly correlated (negative) for spring 1996. None of the species show significant relationships with grain size (Table 5.4). With the exception of *H. germanica* and *E. williamsoni* which show a positive relationship with the grain sizes ≥63µm and ≥16 - <63µm respectively, all correlations are negative.

The correlation between the metals Al, Fe, Cu, As, Ni and Zn in 1992, 1993, 1994 (As is insignificant) and *E. williamsoni* is negative and significant (Table 5.5, a - e). Only Pb (1994) shows a positive and significant relationship with *A. beccarii*. For 1995 *A. beccarii* is significantly correlated with Cu, and, in 1996 with Al, Ni and Zn (Table 5.4, d and e). *Haynesina germanica*, however, is positively and significantly correlated with the metals Al, Fe, Cu, Ni and Zn.

***ii*) The Erme Estuary**

With the exception of *A. beccarii*, all species (but not including *J. macrescens* and *T. inflata*, which were largely absent) show a significant and occasionally strong correlation with salinity (Table 5.6). *Haynesina germanica* and *E. williamsoni* show a consistent positive, significant correlation profile with salinity. *Elphidium williamsoni*, in particular, shows a strong relationship winter and spring (0.83 and 0.75 respectively). *Miliammina fusca* is negatively correlated for each season, except for summer, when it's assemblage proportions and frequency of dominance were diminished. Significant correlation between salinity and *M. fusca* is only shown for autumn and spring.

Haynesina germanica and *E. williamsoni* are significantly correlated with temperature for winter, spring and summer (Table 5.6) with the latter species being strongly correlated for the winter (0.82). *Jadammina macrescens* is only significantly correlated for the winter.

There are no significant correlations between any species and percentage organic carbon. With the exception of *M. fusca* (0.77) there is no significant relationship shown between the C/N ratio and any other species. Each of the three calcareous species show a negative relationship with the C/N ratio and percentage organic carbon.

Ammonia beccarii and *M. fusca* each show a significant relationship (0.62 and -0.55 respectively) with the grain size categories $\leq$16µm and $\geq$16 - <63µm respectively. There are no significant correlation coefficients shown between the metals and any species (Table 5.7).

iii) The Fowey Estuary

All species, with the exception of *M. fusca*, show a change in the level and type (+ or -) of significance with each seasonal salinity profile (Table 5.8). *Miliammina fusca* shows a consistent negative and significant relationship with salinity, which is particularly strong for the autumn and spring (-0.71 and -0.79 respectively). *Elphidium williamsoni* and *A. beccarii* show positive correlations for all seasons, but which are only significant for autumn, winter and summer. *Haynesina germanica* is strongly and positively correlated with salinity for spring.

Miliammina fusca is significantly correlated (negatively) with temperature for all seasons (Table 5.8) and for winter the relationship is strong (-0.74). *Ammonia* *beccarii* is similarly significantly correlated but the relationship is positive for each of the seasons except spring. *Haynesina germanica* is only strongly correlated with temperature for the spring. *Elphidium williamsoni* is significantly correlated for winter and summer.

In general, there is a variable relationship shown between percentage organic carbon and species (Table 5.8). *Haynesina germanica* shows only one significant correlation with organic carbon (winter) and *E. williamsoni* and *M. fusca* are only significantly correlated for the autumn. *Ammonia beccarii* shows no significant relationship with carbon. The relationship between species and the C/N ratio is in most cases, insignificant. *Elphidium williamsoni* shows a negative, significant correlation for the autumn, and *A. beccarii* is similar with respect to spring. There are no significant relationships shown between any species and the three grain size categories (Table 5.8). *Miliammina fusca* is negatively correlated with each of the categories. *Ammonia beccarii* shows the highest correlation (-0.41) and *E. williamsoni* shows the weakest.

iv) The Avon Estuary

Haynesina germanica is significantly correlated with salinity for winter and spring, and strongly correlated for summer (0.7). *Elphidium williamsoni* and *M. fusca* are significantly correlated with salinity for the winter and strongly correlated for the summer (Table 5.10). *Miliammina fusca* is dissimilar to *E. williamsoni* in that it is negatively correlated for each season, except autumn.

Elphidium williamsoni and *M. fusca* are strongly correlated with temperature for summer, the latter species being negatively associated (Table 5.9). This is similar to the salinity correlation profile. *Haynesina germanica* shows a positive and significant relationship with temperature for spring and summer. As with salinity, *A. beccarii* and *J. macrescens* are not significantly correlated with temperature.

In general, a weak relationship is shown between species and percentage organic carbon and most values are approaching neutral. Only *E. williamsoni* (spring) and *J. macrescens* (winter) show a significant relationship (Table 5.10). *Jadammina macrescens* shows a significant relationship with the C/N ratio, for autumn, summer and particularly winter, which is strongly correlated (0.76). *Miliammina fusca* is negatively and strongly correlated only for the winter. *Elphidium williamsoni* (winter) and *A. beccarii* (spring) show a positive and significant relationship with the C/N ratio. There is a significant relationship shown between with the <16µm grain size category and the proportions of *A. beccarii* (0.6), which is similar to that shown by the Erme data. All other correlations are insignificant.

Haynesina germanica is negatively correlated but not significantly, with all metals (Table 5.11), the highest value being for Ni (-0.48). *Elphidium williamsoni* and *A. beccarii* are significantly correlated with Ni, which is particularly strong with respect to the latter species (-0.85). *Ammonia beccarii* shows a less than significant relationship with Al (-0.53). With the exception of Pb, *M. fusca* is negatively correlated with each metal, but in all cases the relationship is insignificant.

5.7 Distribution of the agglutinated species

5.7.1 Introduction

Analysis has been carried out to identify the relationship between the distribution of the agglutinating foraminiferal species and the environmental variables such as salinity, temperature, sediment geochemistry, grain size range, mineralogy and C/N ratios (where available). Ultimately, the results have been used to identify those factors which may account for the observed distribution of the agglutinated species.

5.7.2 Environmental variables and the distribution of the agglutinated species

As previously mentioned (Section 5.4.2, *i*), samples from Restronguet Creek did not contain agglutinated species, living or dead. However, such species colonise the upper estuary and subsidiary creeks of each control estuary with *Miliammina fusca* being the dominant and most abundant of these species (*Jadammina macrecsens* and *Trochammina inflata* were subordinate species within the mid-estuary). The short cores taken from Restronguet Creek also had no agglutinated species (Stubbles *et al.*, 1996a, b) and, as a 50cm core represents approximately 50 years of sedimentation (1cm^{-yr}), this would suggest that the absence has coincided with the working life of the modern Wheal Jane tin mine (Chapter One, Section 1.5.2) and a period of abandonment immediately before this (post - 1945). This period of sedimentation was determined by Dr. G. Hendry who took cores to the same depth, at a similar location and estimated the age using ^{137}Cs (Dr. G. Hendry, Department of Earth Sciences, Birmingham University, pers. comm., 1993). However, the short cores (sedimentation period unknown) taken from the Erme Estuary, E6 and E8 (core lengths of 45cm and 50cm respectively) had agglutinated foraminifera throughout. The core taken from the Fowey Estuary does, however, show a marked anomoly in that *M. fusca* is absent below the 34cm depth which represents an approximate date of 1885 (Pirrie *et al.*, 1999) but the maximum depth of this absence may not be determined from this core as the borer only penetrated to 40cm before reaching a barrier.

The surface samples collected as part of a reconnaissance survey of other South West England estuaries showed that there is a widespread absence of the agglutinated species within the environs of Carrick Roads (Figure 1.4) and in the Kingsbridge Estuary (Figure 1.3). The other reconnaissance sample locations (Yealm, Looe and Axe), however, each contained the six euryhaline species to give a typical estuarine faunal distribution similar to that of the Erme, Fowey and Avon estuaries (Section 5.4.2, *ii - iv*).

The Kingsbridge Estuary (a coastal embayment) and the tributaries (Figure 1.4) of the Carrick Roads (Mylor Creek, Pill Creek, Percuill Creek and St Just in Roseland) each had elevated salinity gradients (>30‰) throughout each estuary, probably exceeding the tolerance limits of the agglutinating species (<25‰), which may account, in part, for their absence. This is supported by the correlation coefficients which show *M. fusca* to be negatively associated with salinity and temperature (Section 5.6, *ii - iv*). The sample stations at Truro, St Clements, Ruan Lanihorne and Tressillian also had an all - calcareous species assemblage (as stained and empty tests), but each had lower salinity regimes which were within the tolerance limits of these species. The salinity and temperature data (Chapter Four, Section 4.3) from the control estuaries (Erme, Fowey and Avon) were similar to those of Restronguet Creek, Truro, St Clements, Ruan Lanihorne and Tressillian. Water temperature gradients in each estuary were similar with the exception of the Kingsbridge Estuary which was a few degrees warmer throughout the estuary, during all seasons. This may be the result of reduced channel water volume and flow (due to catchment loss) which is cooler than the warmer tidal water. Comparing the C/N ratio data (as an indication of nutrient supply in an available form, Chapter Four, Section 4.6) it is evident that the values obtained for Restronguet Creek are similar to the control data and St Clements (C/N ratio of 9.03).

The sample stations in Carrick Roads generally had higher sediment metal concentrations relative to the Erme, Fowey and Avon estuaries (Bryan and

Langstone, 1992). Geochemically, the stations at Mylor, Pill and Truro were similar to Restronguet Creek, having been directly influenced by past metal mining and/or smelting. The stations at Tresillian, Ruan Lanihorne, Percuill and St Just in Roseland do not drain metalliferous mining regions and consequently had marginally lower sediment metal concentrations relative to Restronguet Creek (Yim, 1972; Bryan and Langston, 1992; Sommerfield *et al.*, 1994a,b; Pirrie *et al.*, 1999). The smelters that once operated at Truro emitted airborne contamination which can be more pervasive and persistent relative to surface water conduits (Meetham, 1950; Thomas, 1962; Ida *et al.,* 1966; Rose *et al.*, 1979; Franzin and McFarlane, 1980). As a consequence of this, the smelters at Truro may have contributed towards the contamination levels elsewhere, particularly at nearby St Clements which has sediment metal concentrations which are similar to Restronguet Creek, with the exception of zinc (Appendix 1.1c). Contaminated water originating from Restronguet Creek and the Truro River to the south may also have been tidally introduced northwards into the Tresillian River (Pirrrie *et al.*, 1997).

Other factors which may limit the distribution of the common agglutinated species (e.g., *M. fusca*) are the mineralogy and grain size range of the sediment inhabited by these shallow infaunal protists (Chapter Four, Section 4.4). The material used for test construction has been compared with contemporaneous sediment samples by using scanning electron and transmitted light microscopy techniques. This comparative analysis has concentrated on tests of *M. fusca* as it is the commonest of the agglutinated species in the control estuaries and also because *J. macrescens* and *T. inflata*, with the exception of the area around the aperture, show much less variation in the grain size and type of mineral used for test construction (Chapter Three, Plates 2 and 3). The latter two species show a preference for flat minerals such as mica and clay, which are methodically rather than randomly arranged. The area around the aperture of both species is much less well ordered. These preliminary investigations would suggest, therefore, that these two species show selectivity with respect to grain size and mineralogy, which may be limiting factors in their distribution. The scanning electron micrographs (Plate 1, Figures 1 - 5 [Chapter Three], Plate 7, Figures 1 - 4 and Plate 8, Figures 1 - 9) show examples of *M. fusca* constructed with a variety of mineral types and a wide range of grain sizes, which are randomly arranged. The specimen of *M. fusca* featured in Plate 7 (Figures 1 - 4), from the Fowey Estuary, is a commonly occurring example of coarse grained test agglutination (4 - 70µm) using the minerals, quartz, biotite and muscovite mica, detrital clay, and more rarely, diatom frustules, tourmaline, apatite and cubic pyrite, all of which are present in the sediments and may have been tidally introduced from St Austell Bay which historically received china clay waste via. Par (Bristow and Scott, 1998; Scott *et al.*, 1998; Pirrie and Camm, 1999) and from the kaolinised parts of the Bodmin granite. Sediments from the Fowey Estuary have a grain size range and distribution which is intermediate between Restronguet Creek, and the Erme and Avon estuaries (Chapter Four, Section 4.4.2, *i*, *ii*, *iii*, *iv*). Specimens of *M. fusca* from the Erme and Avon estuaries generally had finer grained agglutination (4 - 10µm), irrespective of there being lower proportions of material <16µm (the observed average size of material used by *M. fusca*) in the contemporaneous sediment samples relative to the other locations. The minerals biotite and muscovite mica, quartz, detrital clay and diatoms used to construct tests from the Erme and Avon estuaries reflect the respective sediment mineralogy. Analysis carried out by Prof. M. B. Hart (University of Plymouth) on specimens of *M. fusca* from the Erme Estuary in 1991 (S. J. Stubbles, unpublished undergraduate dissertation) has shown that some tests were constructed almost entirely of pennate diatom frustules. The more recent samples taken in 1993 did not show a recurrence of this phenomenon which probably reflected an episodic and unusually high abundance of diatoms. The only part of the outer test displaying grain size and mineral selection is in the construction of the apertural tooth which is finely agglutinated with clay and mica flakes. The inner whorl of *M. fusca* from each estuary is exclusively constructed of fine grained material less than 5µm across. This is the different to the analysis carried out by Brönnimann and Whittacker (1988c) which found the inner walls of *T. inflata* to be more coarsely agglutinated relative to the outer layer. The authors also found that agglutinated species formed tests, in the 'agglutinated phase', that were either 'differentiated' (*T. inflata*) or 'undifferentiated' (no sorting or grain arrangement). Overall, lithic clasts have not been used for test construction, despite their high abundance in sediments from the Fowey, Erme and Avon estuaries.

It was evident by the colour, high mica and clay content of the sediments taken from Tresillian and Ruan Lanihorne, and to a much lesser extent St Clements, that the drainage catchment is extensively influenced by china clay extraction (Hosking and Obial, 1966). With the exception of St Clements, which had abundant stained foraminifera, the locations at Tresillian and Ruan Lanihorne usually yielded few stained foraminifera which suggests that physical as well as chemical disturbance may have occurred. Both the species distribution at St Clements and the sediment grain size were similar to Restronguet Creek, but the mineralogy of the sediment sample was distinctly different, being similar to that of the Fowey Estuary (Plate 6, Figures 4 and 5). The sediment sample from St Clements had abundant shell fragments (reflecting above neutral pH of the pore and river/tidal water), detrital clay, quartz, biotite and muscovite mica, kaolinite books and lithic clasts (Plate 5, Figures 6 - 8). Occasionally, a few stained specimens of *Jadammina macrescens* have been collected from St Clements but these were infrequent and low in abundance.

Plate 7

Agglutinated foraminiferal tests - Fowey Estuary

Figure 1. Test wall and aperture view of *M. fusca*, Fowey Estuary, StW2, spring 1994. Showing wide variation in sediment grain size and mineral type used to construct the test. The elongate mineral is probably tourmaline (T).

Figure 2. Enlargement of the aperture in Figure 1, showing a grain of tourmaline.

Figure 3. Enlargement of the wall of *M. fusca* (also shown by Plate 1) material shown includes mineral grains of topaz? (Tp) and mica flakes (M).

Figure 4. Enlargement of the wall in Figure 3, mineral examples of quartz (Q), mica flakes (M), detrital clay and a pennate diatom frustule (D).

Plate 7

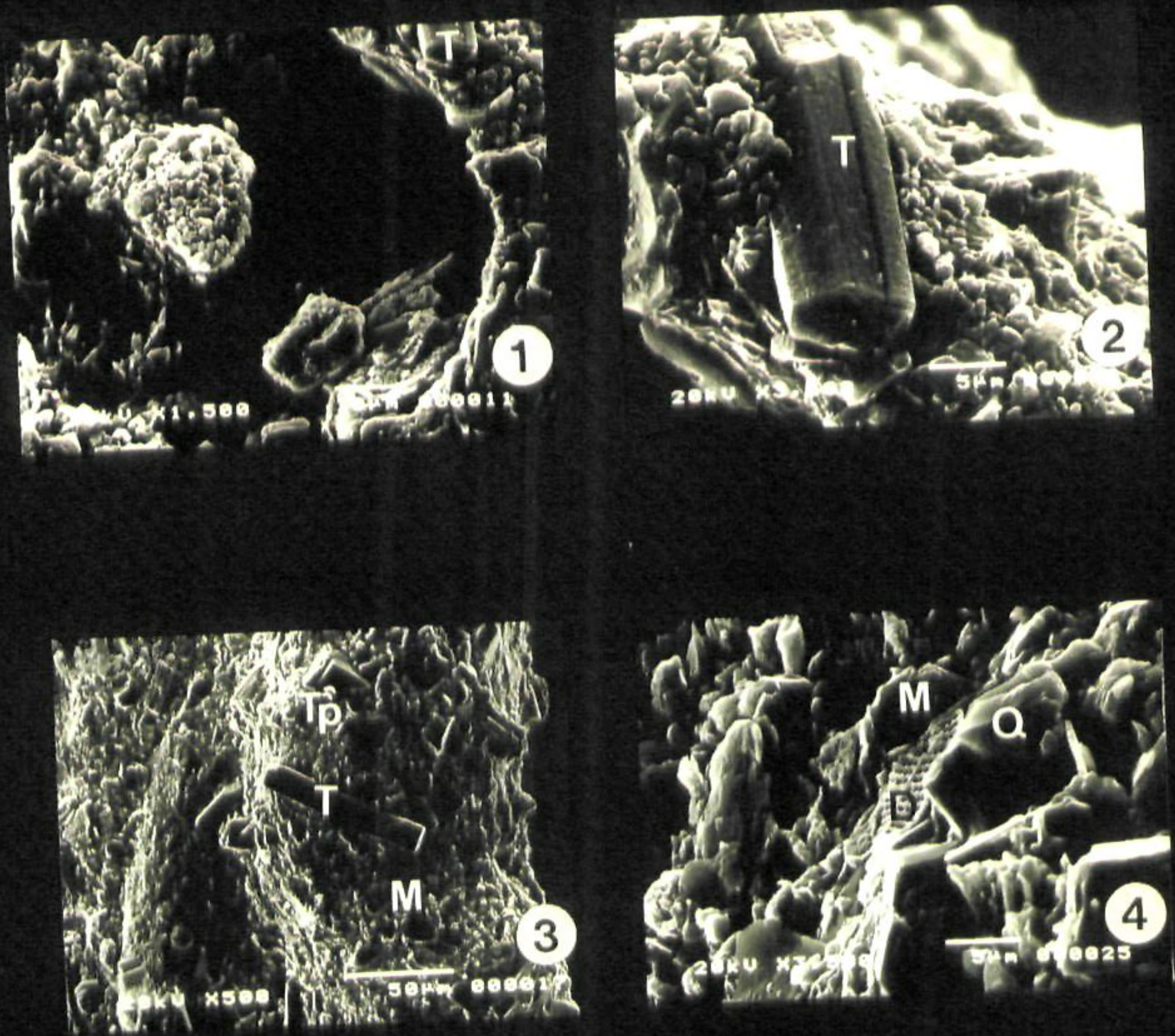


Plate 8

Agglutinated foraminiferal tests - Erme and Avon esturies

Figure 1. *Miliammina fusca*, Avon Estuary, station A3, summer 1995. Low magnification view showing the agglutinated wall.

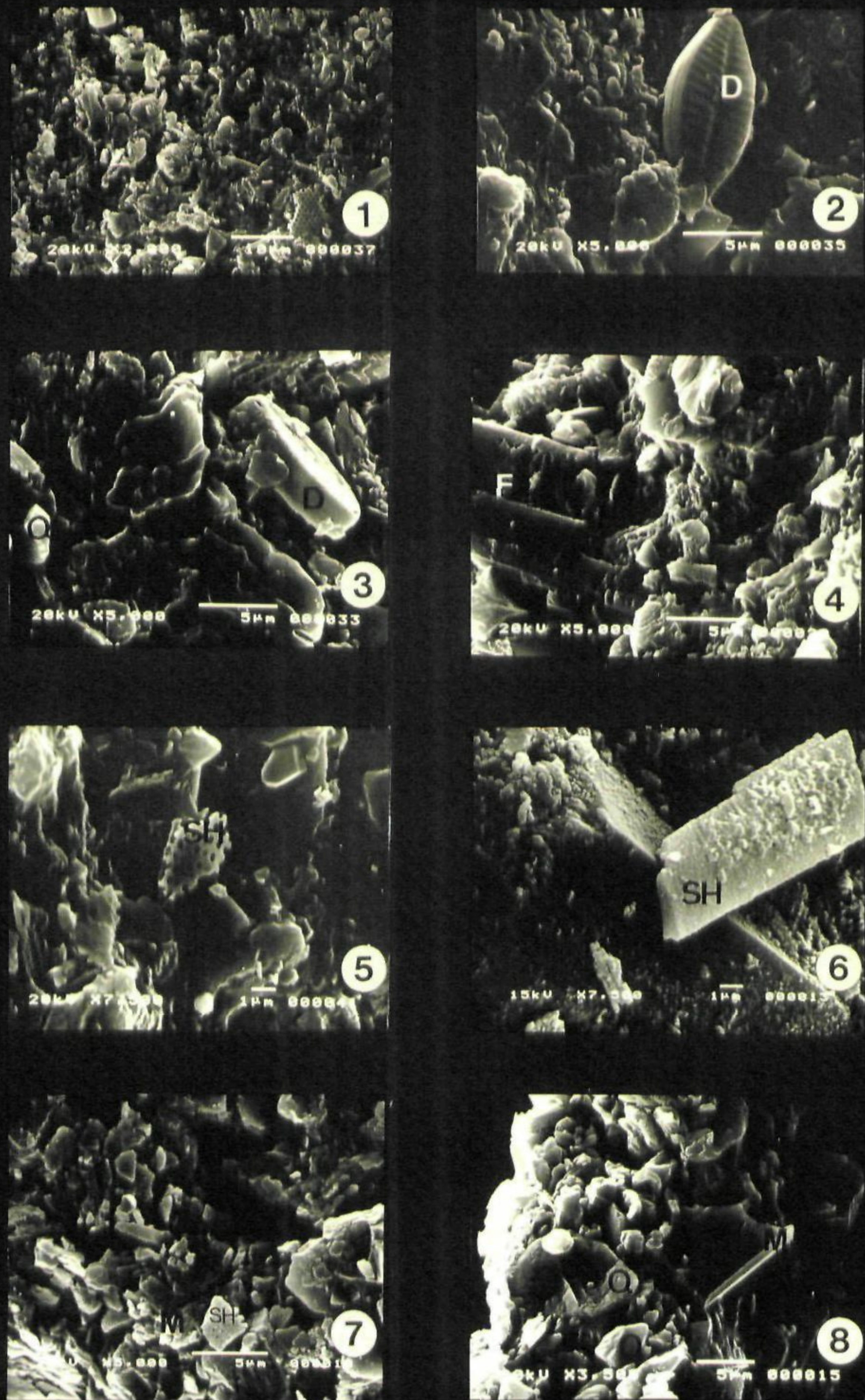
Figure 2. Enlargement of intact pennate diatom frustule (D) in Figure 1.

Figure 3. Enlargement of Figure 1, showing a mixture of mineral and organic debris used to construct the test, diatom (D) and quartz (Q).

Figures 4 and 5. View of test wall (specimen as in Figure 1) showing the variation in the size of material and the type of material used (quartz, feldspar {F}, detrital clay, mica and shell fragments {SH}).

Figure 6, 7 and 8. *Miliammina fusca*, Erme Estuary, station E5, autumn 1993. Mineral and biogenic grains of quartz (Q), mica (M) and shell fragments (SH) used to construct the test.

Plate 8



In summary, therefore, salinity regimes may account for the absence of the agglutinated species in the creek locations of Mylor, Percuil, Pill and the estuarine location of St Just in Roseland. The other locations in Carrick Roads, however, have salinity regimes which are comparable to those of the control estuaries, Erme, Fowey and Avon. With respect to sediment metal concentrations, the locations at Truro and St Clements each had sediment metal concentrations which were similar to Restronguet Creek. It is apparent that the mineralogy of the sediment samples is reflected by the tests from each location but that the available grain size appears to be less significant. The abundance of mica and clay particles and the high proportions of fines (<16µm), particularly in Restronguet Creek, would provide ample suitable material for test growth by such species as *J. macrescens* and *T. inflata*. Little is known, however, of the extent to which agglutinated foraminifera select the material used to build their tests. Slama (1954) concludes that *Ammobaculites* was not selective if the available material is limited and Scott *et al.* (1998) found that *M. fusca* showed no selectivity in grain size, shape or mineralogy. Wightman (1990a), however, found that the three species *A. subcretaceous*, *A. coprolithiformis* and *A. obliques* were grain-size selective which was controlled by 'architectural' constraints and the grain size of the facies inhabited. Wightman (1990a) conceded that these preferences were only applicable to fossil assemblages and had not been recorded in Recent assemblages. Medioli *et al.* (1987) found that the taxonomic value of test material was of limited use and conclude that the material used to build the test depends on what is available and this appears to be the case in samples used in this study.

5.8 Test deformity

5.8.1 Introduction

Test deformity, although occasionally displayed by *Miliammina fusca* and *Trochammina inflata*, has not been attributed to metal pollution as the micro-analysis techniques available cannot take account of the numerous unknown factors associated with tests built of heterogeneous material (Section 5.7). Reliable instrument and elemental calibration have been achieved with respect to the calcareous species with quantified data being obtained using Laser Ablation ICP (Section 5.9) and semi-quantitative data using SEM microprobe (Stubbles *et al.,* 1996a). Specimens of *Jadammina macrescens*, without collapsed chambers (natural deformation), have also displayed test deformity but only occasionally. However, due to frequently occurring natural deformation (Chapter Three, Plate 2, Figure 6), this species is not suitable for this type of study. Hence, only the forms of the test and percentage proportions of test deformity are described here with respect to the calcareous species standing crop. This prevents either elevation or reduction of the proportions of test deformity in the control estuaries relative to Restronguet Creek where the agglutinated species are absent. Deformity abundance data are given in Appendix 2.1 - 2.4 and give values that include deformed calcareous tests and total deformed tests; the latter including deformed agglutinated species.

5.8.2 Types of test deformity

The types of test deformity described here appear in each of the sampling locations but the more extreme forms (e.g. multiple chambered) are more common and abundant in Restronguet Creek. Because of the subjective nature of the analysis, quantitative data have not been obtained, and only the obvious examples of test deformity (omitting those tests with mechanical damage) have been included in this analysis. For objective analysis a computerised analysis of at least 35 specimen examples of each type of deformity is required (Dr. N. McCleod, The Natural History Museum, London, pers. comm. 1995) which is beyond the scope of this research. Occasionally, acute test deformation has obscured the taxonomic features of certain species, making identification doubtful. Included with the examples of test deformity (Plates 9 - 13) are juvenile specimens with deformed tests which only occurred in the Restronguet Creek samples (those specimens retained on the 63µm sieve and, hence with a test size <125µm). These deformed specimens are distinct from the naturally occurring irregular forms which are common in the tests of juveniles.

For the purposes of this research the types of deformity have been grouped according to the predominant structural feature with the exception of the combination type. There are nine types of deformity described here; combination, additional calcareous growth, protruding last chamber, twinning, enlarged final chamber, high trochospiral, notched periphery, multiple chambers and reduced chamber size. The largest group type is the 'combination'; i.e., where more than one form of deformity is exhibited (Plate 9, Figures 1 - 12, and Plate 10, Figures 1 - 6). The second most abundant group are those tests displaying additional calcareous growth which is a calcareous adhesion, commonly appearing as a sphere (Plate 10, Figures 7 - 14). An uncoiling of the test during the last stages of growth is termed 'protruding last chamber' and is displayed more commonly by the species *H. germanica* (Plate 11, Figures 1 - 3) and less so by *E. williamsoni*. This deformity has not been noted in *Ammonia beccarii*. Twinning has rarely been displayed by *A. beccarii* but is more commonly found in specimens of *E. williamsoni* and *H. germanica*. The more extreme examples of twinning are shown by Plate 11 (Figures 4 - 7).

Plate 9

Figures 1 - 12: Combination

(all specimens for Plates 10 - 14 were taken from Restronguet Creek, stations TC6, TC8 and TC9 at various time intervals)

Figure 1. *Haynesina germanica*, displaying a combination of additional calcareous growths, notched periphery and mis-shapen sutures.

Figure 2. *Haynesina germanica*, with mis-shapen sutures and chambers.

Figure 3. *Haynesina germanica* displaying more subtle deformed features, one enlarged mid-chamber and acutely arched sutures.

Figure 4. *Haynesina germanica* displaying several deformed features, in particular, an enlarged last and penultimate chamber.

Figure 5. Juvenile, *H. germanica*, with an enlarged mid-chamber and reduced number of tubercles.

Figure 6. *Haynesina germanica* with several bulbous chambers.

Figure 7. *Ammonia beccarii*, spiral side, with enlarged final chamber, the other chambers are irregular with respect to size and shape.

Figure 8. *Ammonia beccarii*, spiral side with irregular chamber shape.

Figure 9. *Ammonia beccarii*, spiral side, with irregular chamber size and shape particularly in the earlier formed chambers.

Figure 10. *Ammonia. beccarii*, spiral side, with irregular chamber size and shape particularly in the later formed chambers.

Figure 11. *Ammonia beccarii*, spiral side, with disproportionately smaller final chamber. The other chambers are of irregular size, which produce an elongate test.

Figure 12. Juvenile, *A. beccarii*, umbilical side, with a deep depression between the final and penultimate chambers.

Plate 9

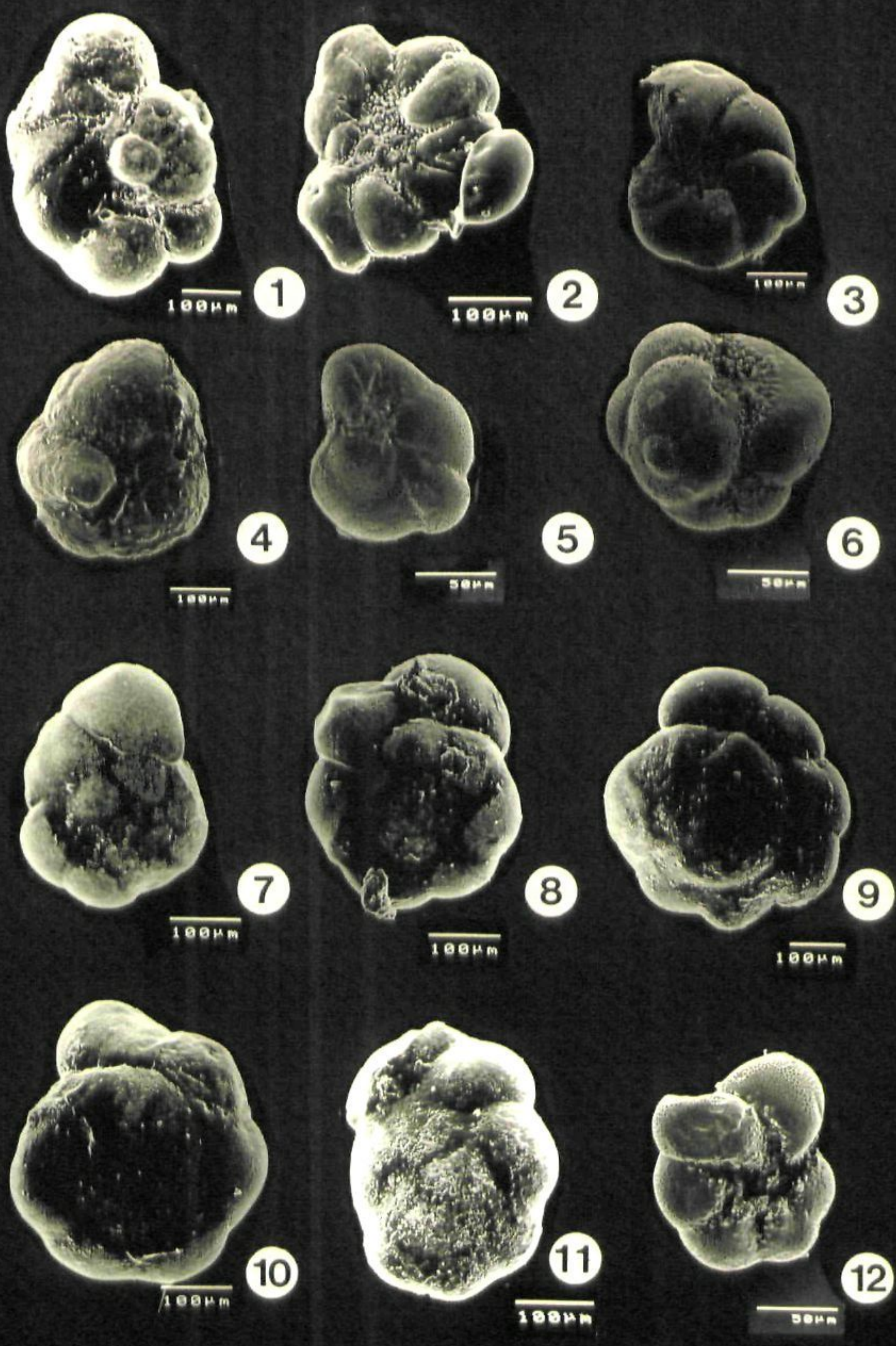

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Plate 10

Figures 1 - 6: Combination

Figure 1. *Elphidium williamsoni*, with a combination of disproportionately sized chambers, forming a notched periphery and mis-shapen sutures.

Figure 2. *Elphidium williamsoni,* with a combination of a notched periphery, mis-shapen sutures and chambers.

Figure 3. *Elphidium williamsoni* with a protruding mid-chamber and additional calcareous adhesions around the apertural face.

Figure 4. Juvenile *E. williamsoni* (?) with enlarged last chamber but flattened penultimate chamber. The sutures have fewer retral processes.

Figure 5. Juvenile *E. williamsoni* with inflated earlier formed chambers. The sutures and retral processes are deformed with the latter being few in number.

Figure 6. *Elphidium williamsoni* with an acutely arched and re-orientated suture.

Figures 7 - 14: Additional Calcareous Growth

Figure 7. *Elphidium williamsoni* with a calcareous protrusion of two chambers.

Figure 8. *Elphidium williamsoni* with irregular chamber extension of the test.

Figure 9. *Haynesina germanica* with additional calcareous growth of two chambers.

Figure 10. *Haynesina germanica* with additional and irregular chamber size.

Figure 11. *Haynesina germanica*, as above.

Figure 12. *Haynesina germanica* with additional calcareous growth.

Figure 13. *Haynesina germanica* as above.

Figure 14. Juvenile *A. beccarii* with additional calcareous growth and mis-shapen chambers.

Plate 10

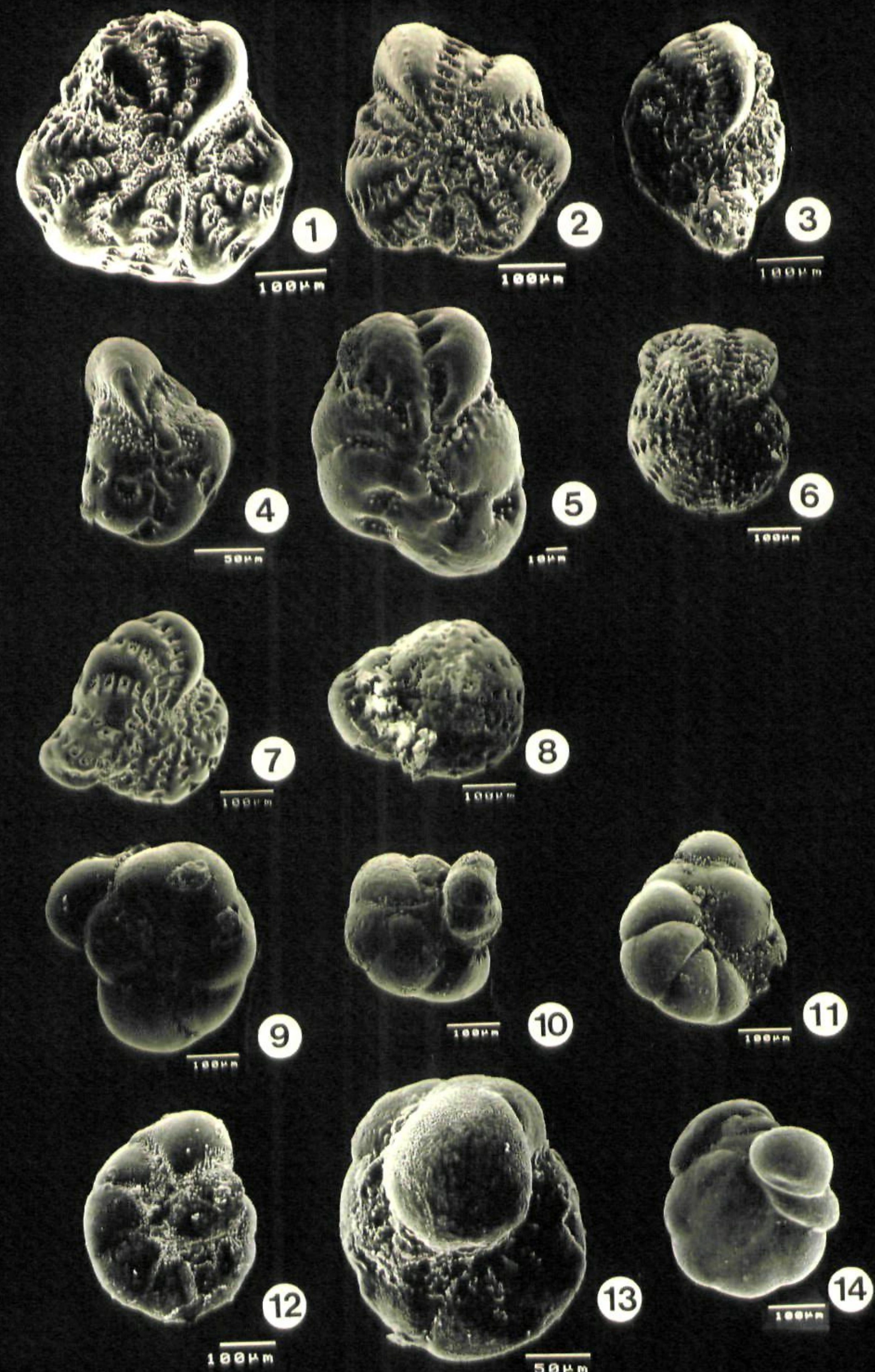
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Plate 11

Figures 1 - 3: Protruding Chamber

Figure 1. Juvenile *Haynesina germanica*, with a protruding additional chamber.

Figure 2. *Haynesina germanica*, with an enlarged, extended and re-orientated final chamber.

Figure 3. *Haynesina germanica*, with an elongated test.

Figures 4 - 7: Twinning

Figure 4. Twinned *E. williamsoni.*

Figure 5. Twinned *E. williamsoni*, with a double aperture.

Figure 6. Twinned Juvenille *E. williamsoni*, with a reduced number of retral processes.

Figure 7. Twinned *H. germanica.*

Figures 8 - 12: Enlarged Final Chamber

Figure 8. *Haynesina germanica*, with enlarged sets of mid and final chambers.

Figures 9 - 11. *Haynesina germanica* with enlarged final chamber.

Figure 12. *Ammonia beccarii* with enlarged final chamber. Spiral side.

Plate 11

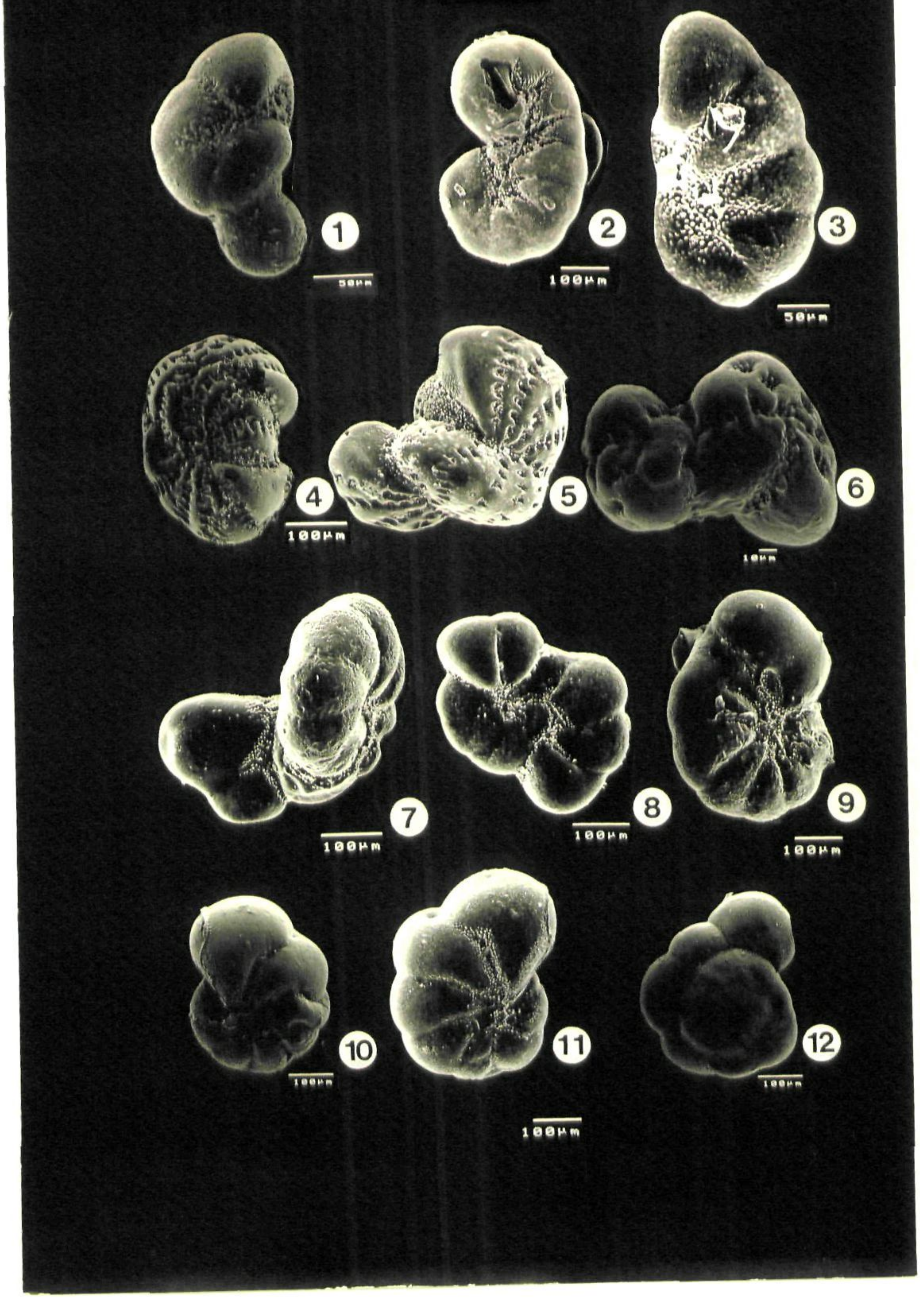
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Plate 12

Figure 1. Enlarged final chamber of *Elphidium williamsoni* with a reduced sized penultimate chamber.

Figures 2 and 3: High Trochospiral

Figure 2. Juvenile *Ammonia beccarii* with over inflated chambers, beginning with the proloculus which extends outwards.

Figure 3. *Ammonia beccarii* with enlarged proloculus.

Figures 4 - 9: Notched Periphery

Figure 4. *Haynesina germanica* with a deep notched periphery.

Figure 5. *Haynesina germanica* with a shallow notched periphery.

Figure 6. *Haynesina germanica* with a re-orientated final chamber and deep notched periphery.

Figure 7. *Haynesina germanica* with notched periphery or reduced growth of a mid-chamber.

Figure 8. *Ammonia beccarii* with a notched periphery. Spiral side.

Figure 9. *Elphidium williamsoni* with notched periphery.

Figures 10 - 12: Multiple Chamber Growth

Figure 10. *Haynesina germanica* with multiple chamber growth displayed in two orientations.

Figure 11. *Haynesina germanica* displaying multiple chamber growth.

Figure 12. *Haynesina germanica* (?) displaying multiple chamber growth.

Plate 12

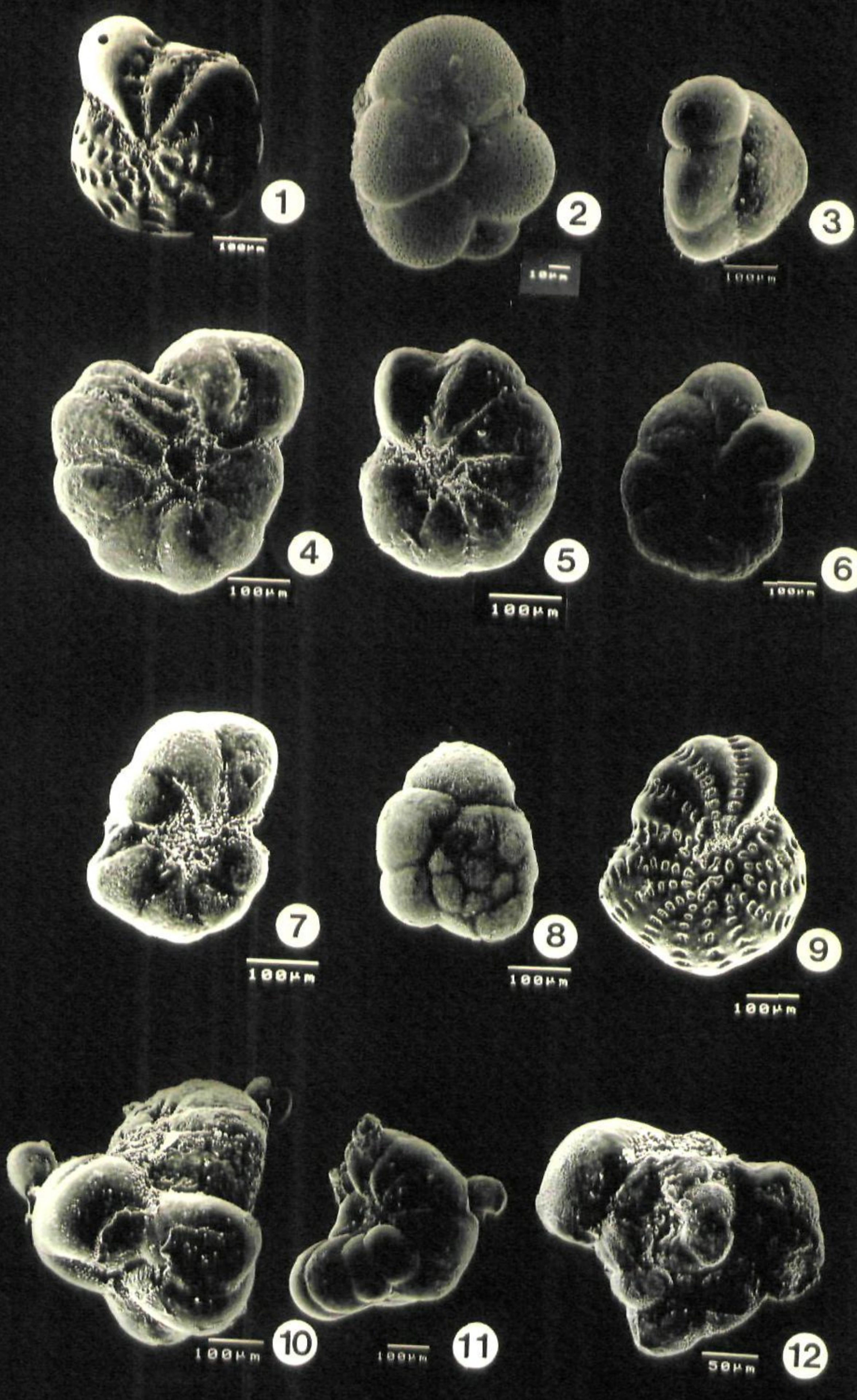
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Plate 13

Figures 1 - 6: Reduced Last Chamber Growth

Figure 1. *Elphidium williamsoni* with a disproportionately smaller last chamber.

Figure 2. *Elphidiuim williamsoni* with a disproportionately smaller last chamber which forms a near discoid test shape.

Figure 3. *Elphidium williamsoni* with a disproportionately smaller last chamber.

Figure 4. *Elphidium williamsoni* with a disproportionately much smaller last chamber and, with an additional calcareous growth.

Figure 5. *Ammonia beccarii* with a disproportionately smaller last chamber. Spiral side.

Figure 6. *Ammonia beccarii* with a disproportionately smaller last chamber. Umbilical side.

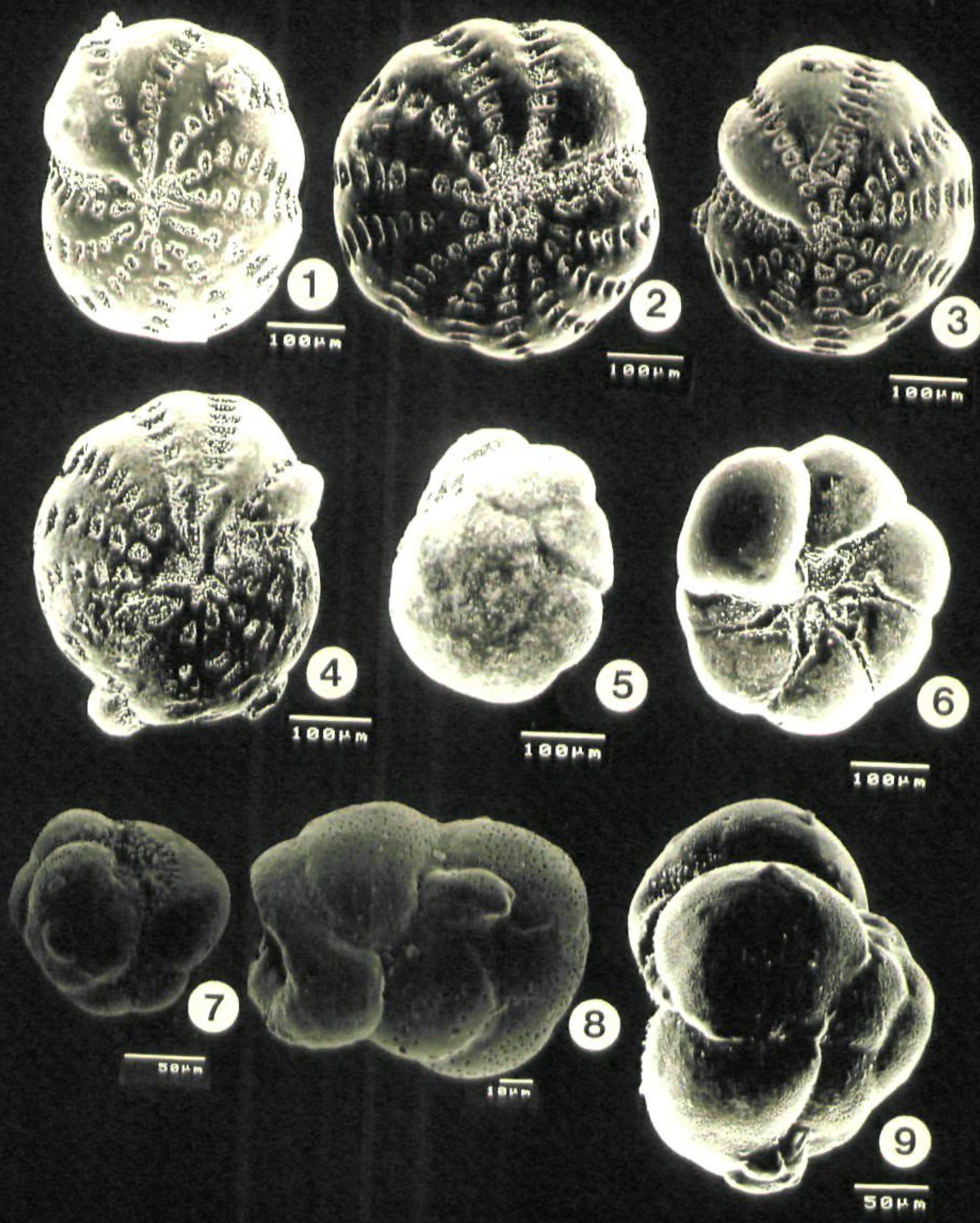
Figures 7 - 9: Acute Deformation

Figure 7. *Haynsina germanica (?)* with irregular chamber size and shape.

Figure 8. *Ammonia beccarii* (?) with irregular chamber and test shape, spiral side.

Figure 9. *Ammonia beccarii* with irregular chamber size and shape. Spiral side.

Plate 13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Tests that have an enlarged final chamber are commonly displayed by *H. germanica* (Plate 11, Figures 8 - 11) and *A. beccarii* (Plate 11, Figure 12) but less commonly by *E. williamsoni* (Plate 12, Figure 1). *Ammonia beccarii* was the only species to display an enlarged proloculus which produces a high trochospiral test (Plate 12, Figures 2 and 3). Tests with notched peripheries (Plate 12, Figures 4 - 9) are exhibited by all species but are particularly common in *E. williamsoni*. Tests with multiple chamber growth create acute distortion of the chambers and sutures (Plate 12, Figures 10 - 12) and appeared more commonly in Restronguet Creek, particularly within the dead assemblage. In some cases this deformity can lead to mis-identification of the species. A disproportionately smaller last chamber (reduced chamber size) relative to the preceding chambers is a deformity displayed by all species and is moderately common (Plate 13, Figures 1 - 6). In the case of *H. germanica* (Plate 13, Figure 5) this type of deformity may be an artifact of the notched periphery. Finally, examples of extreme deformity whereby the taxonomic characteristics of a specimen are obscured, thus leading to species mis-identification, are shown by Plate 13, (Figures 7 - 9) but these forms are rare.

5.8.3 Proportions of test deformity

i) Restronguet Creek

The data for test deformity have been grouped and compared by season to reflect seasonal variation in standing crop density (Section 5.2). Seasonally, the winter, spring and autumn (Figure 5.20 - 5.23, a - b) had the highest frequency occurrence of high values with a range between 7% - 30% particularly in the early stages of sampling (pre - 1994). Although the summer data sets were overall the lowest, there was only one station at which deformed tests were not present (station D1 in 1993). The highest summer values only appear more frequently in 1993

(0% - 56%) but the majority of values were below 7% (Figure 5.23, a and b). In the majority of cases the summer 1995 and 1996 values were less than previously recorded in 1993 and 1994. Station C19 was the only station to have consistently high summer values of between 6% and 56% during each year (Figure 5.23b). Comparing the average values obtained for the years 1992 and 1996 (autumn) the former year was 7% while the latter had 2.5% deformed. Overall, samples taken from the upper (D1) and mid - Creek stations (TC6, TC8, TC9), and the subsidiary creek station, PC13 on the north side (Figures 5.20a - 5.23a) frequently had the highest proportions. On the south side, stations C19, K20 and H23, had the highest proportion of deformed tests (Figures 5.20b - 5.23b) but the frequency was low compared with equivalent stations on the north side. Those stations which were not colonised by foraminifera (Section 5.2) had high proportions of test deformity with the onset of colonisation, for example, D1, with 11% in spring and autumn 1993 (Figure 5.20a - 5.22a), and, station C19 (Figure 5.22b) with 10% in the spring (1993) and 56% in the summer (1993). Station K20, however, had no deformed foraminifera when colonisation began in autumn 1994 but this may be an artifact of the small sample size of 52 stained individuals. There are, however, numerous examples of test deformity observed in low abundance standing crops, most particularly prior to summer 1994 (e.g. TC6 and H23 autumn 1992; D1,TC6, C19 and H23 spring 1993, Appendix 2.1). Station C19 in summer 1993 had a particularly small standing crop of 18 of which 10 were deformed (56%). During the following winter (1995) no samples were taken at C19, K20 and H23 due to flooding but test deformity at K20 was 16% in the summer of 1995 (Figure 5.23b) from a standing crop of 552. Spring 1995 and winter 1996 also had zero test deformity at station K20, but this may be due to the lower standing crop density (70 and 11 respectively).

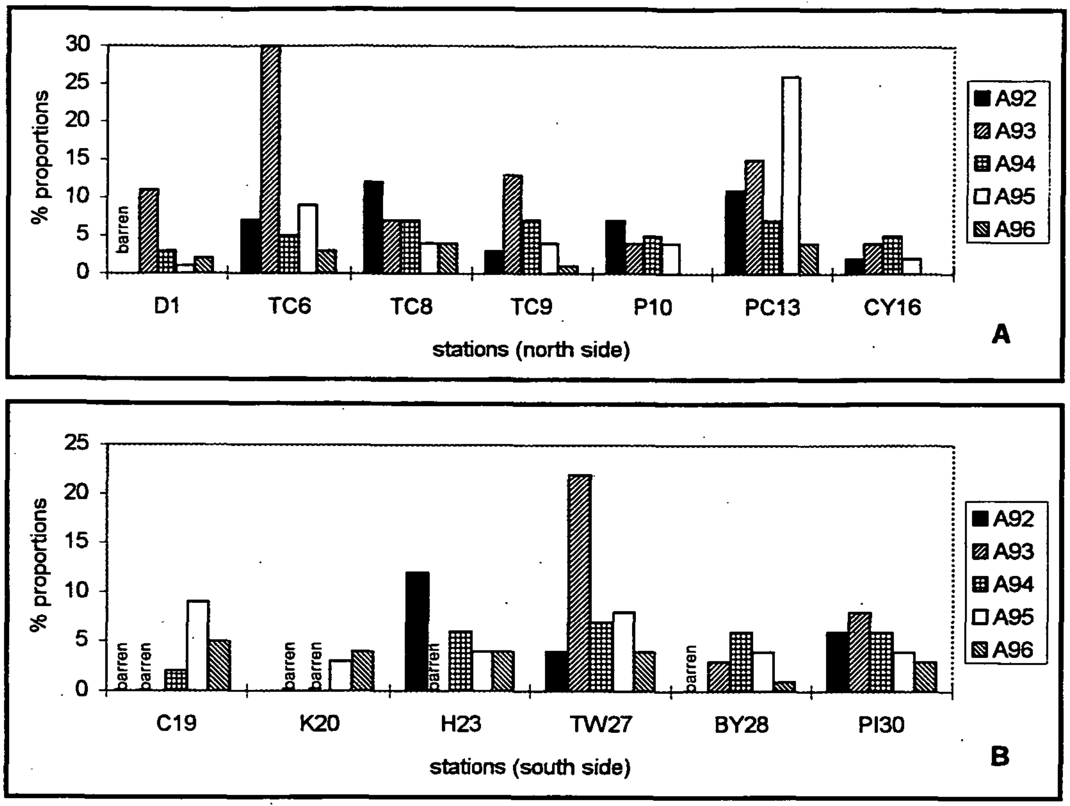


Figure 5.20: Proportions of test deformity in Restronguet Creek, autumn 1992 - 1996. a) north side and b) south side.

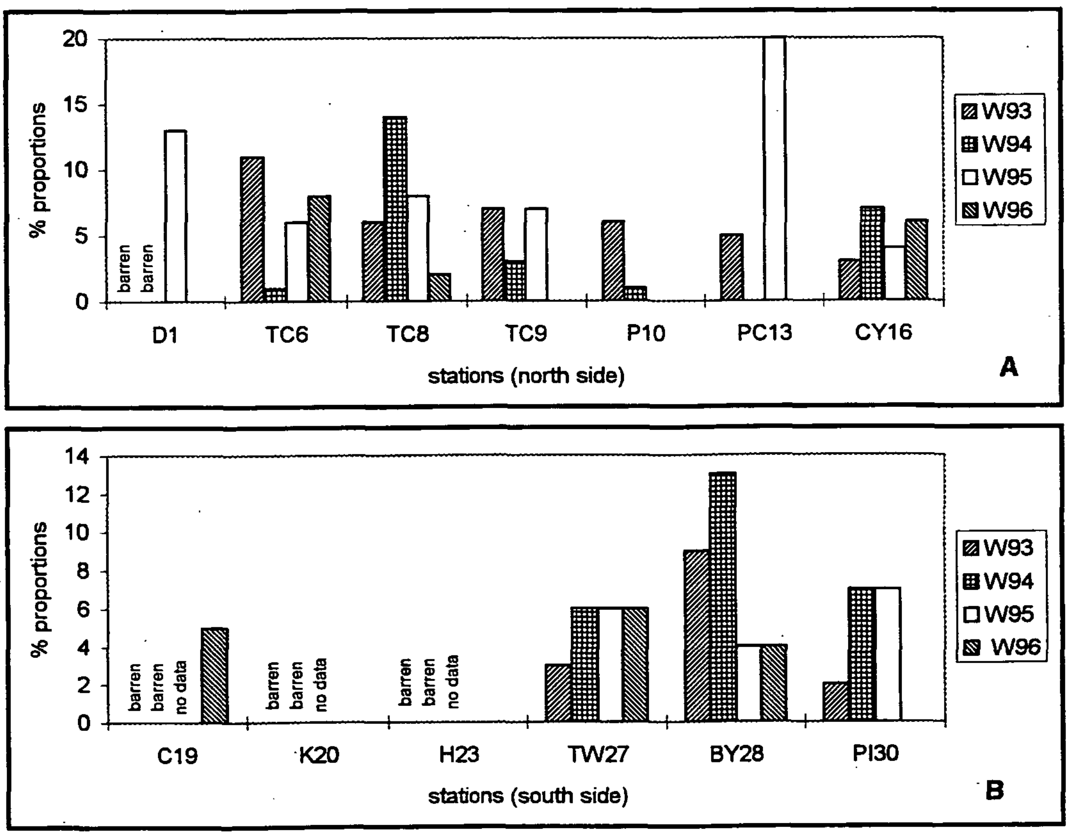


Figure 5.21: Proportions of test deformity in Restronguet Creek, winter 1993 - 1996. a) north side and b) south side.

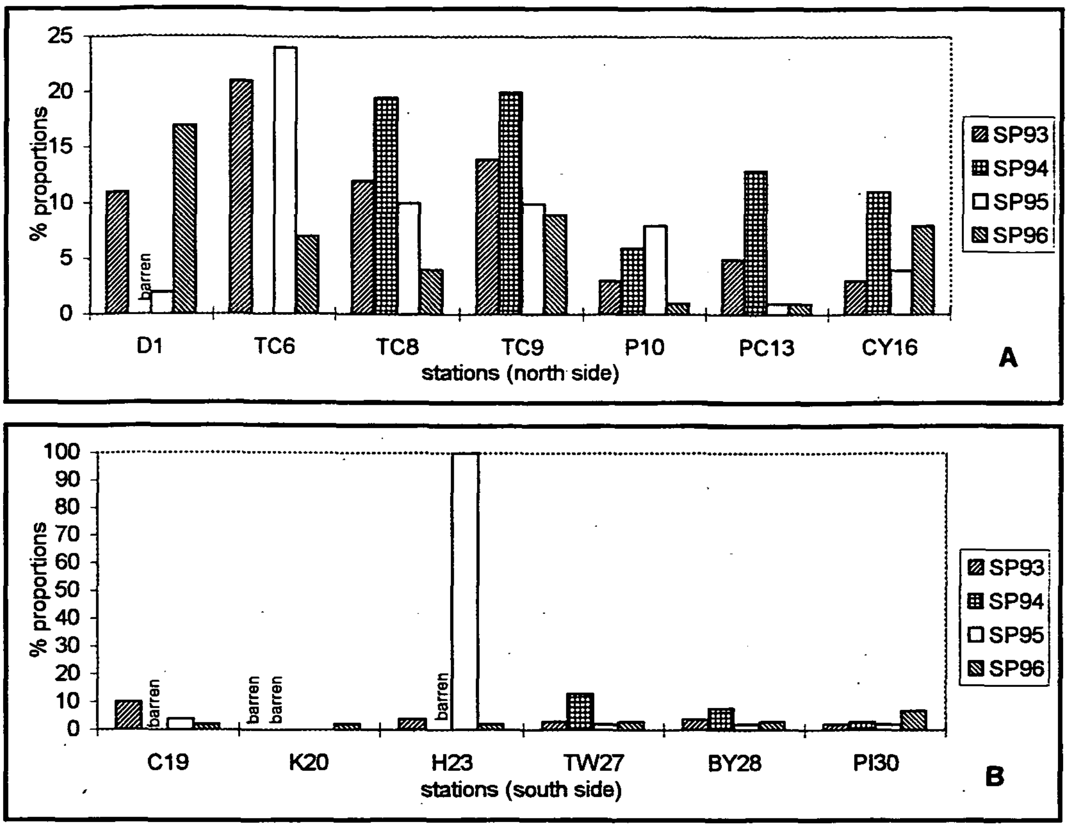


Figure 5.22: Proportions of test deformity in Restronguet Creek, spring 1993 - 1996. a) north side and b) south side.

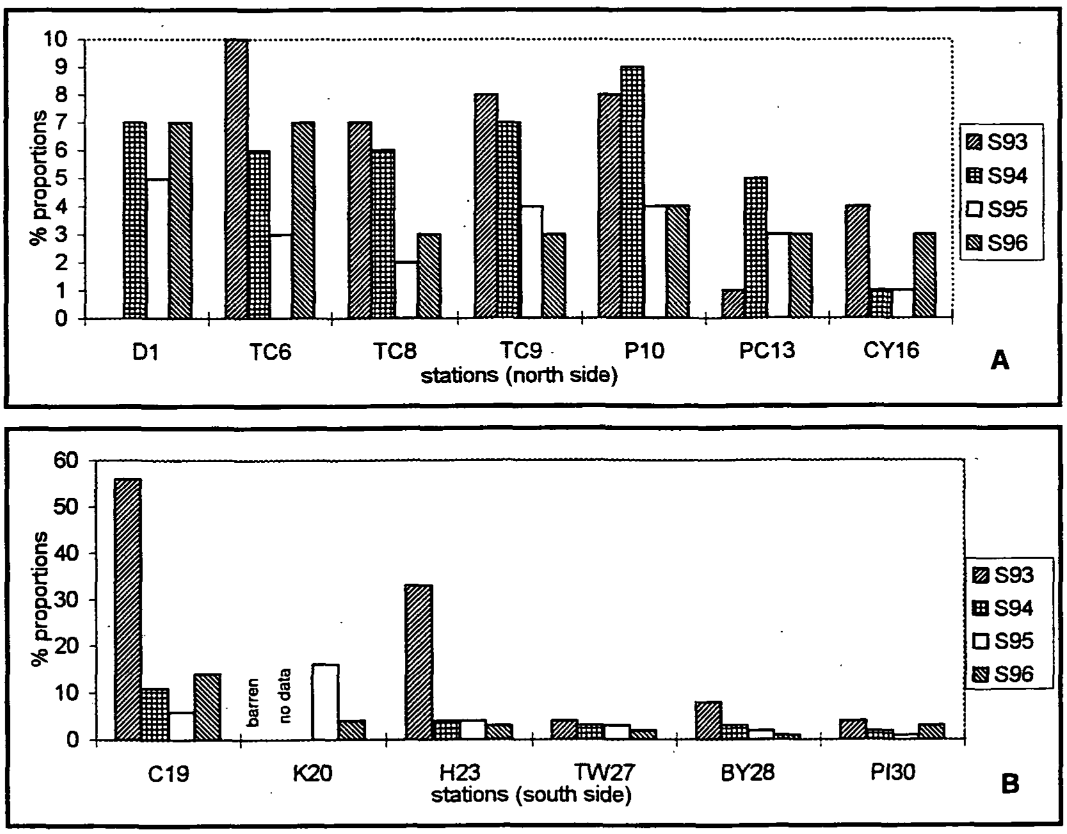


Figure 5.23: Proportions of test deformity in Restronguet Creek, summer 1993 - 1996.a) north side and b) south side.

The distribution of test deformity observed for each species broadly follows the trend shown in species dominance with more deformed tests exhibited by the dominant taxa. Prior to summer 1995, the proportions and frequency of *A. beccarii* were low and consequently the portion of the total standing crop that comprised deformed *A. beccarii*, was similarly low. With the increased occurrence of *A. beccarii* the instances of test deformity exhibited by this species has also increased. It is apparent that of the three species the proportions of *A. beccarii* that are deformed is high (e.g., 27% of *A. beccarii* were deformed at station H23, summer 1996).

In summary, therefore, the springs of 1993 and to a lesser extent 1994 and 1995, had frequent occurrences of high percentage proportions of test deformity on the north side but less so on the south side of the Creek. The years 1993 and 1994, and a lesser extent 1992 (autumn only) generally gave the highest percentage proportions throughout the Creek, but the following period 1995 - 1996 had few values greater than 4%. There were numerous occurrences of zero on both sides of the Creek in winter 1996 and the average proportion of deformed tests was less than 3%. The winter average for 1993 was 6%. In the summer of 1996, however, there were no occurrences of zero and values ranged between 3 and 7% (mean of 4%) on the north side, and, 1 and 14% on the south side (mean of 5%).

***ii)* Erme Estuary**

Seasonally, the spring had the highest number of stations which had deformed foraminifera and winter the least. The summer and autumn each had the same number of stations with deformed tests. Stations E5 (4 - 12%) and OW14 (1 - 10%) were the only stations to each have deformed tests during all seasons (Figure 5.24, a and b).

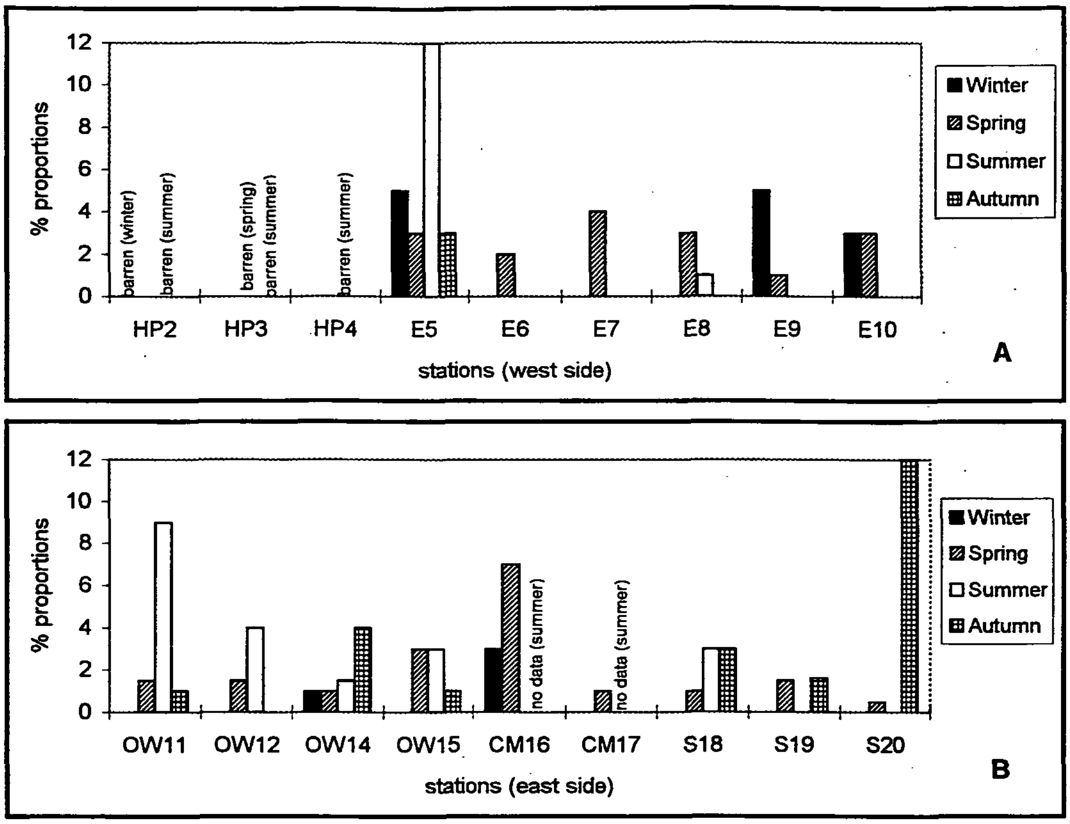


Figure 5.24: Seasonal variation in the proportions of test deformity, Erme Estuary. a) west side and b) east side.

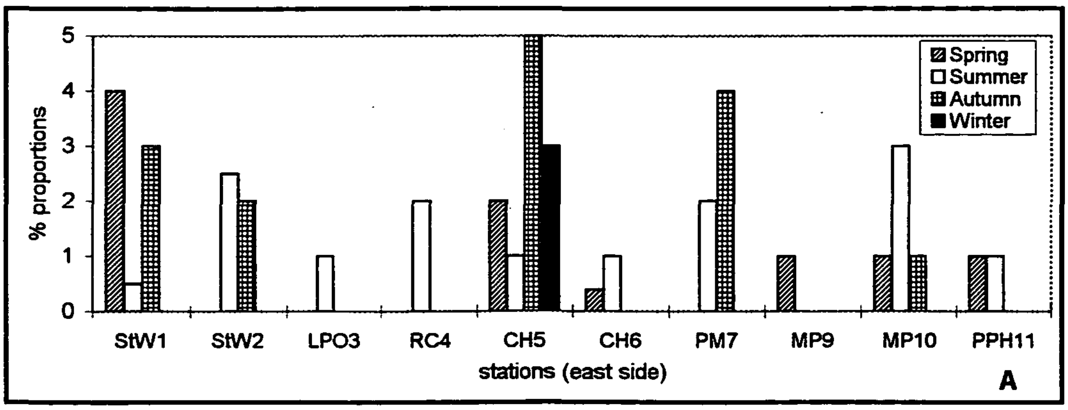
The highest percentage proportion of test deformity in the Erme Estuary was 12% at station E5 in the summer and at station S20 in the autumn of 1993 (Figure 5.24a). Stations OW11 (summer) and CM16 (autumn) each had the second highest value. Otherwise, the majority of values were below 3% with frequent occurrences of zero. The low and mid - estuary stations on the east side (Figure 5.24b) had more frequent occurrences of test deformity relative to the west side but due to the seasonal absence of foraminifera at stations HP2 - HP4 interpretation of the results are constrained due to a lack of data. The average proportions of deformed tests did not exceed 3% and, overall, the occurrence and proportions were randomly distributed.

The deformed species portion of the standing crop total is less influenced by species dominance and it appears that the instances of test deformation by

H. germanica and *E. williamsoni* are similar. The exception to this is for the spring with more *E. williamsoni* having instances of test deformity. There is only one instance of test deformity shown by *A. beccarii* but this species is a minor assemblage componant.

iii) Fowey Estuary

There were no individual values above 5% in the Fowey Estuary (Figure 5.25, a and b) and deformed tests were frequently absent at many stations in the winter, but less so in the summer, autumn and spring when the calcareous species componant was greater. Average proportions did not exceed 2%. Deformed tests were recorded at stations CH5 and G12 for all seasons. Stations StW1 and G14 had between 1% and 5%, and, 1% and 4% deformed tests respectively, in spring, summer and autumn.



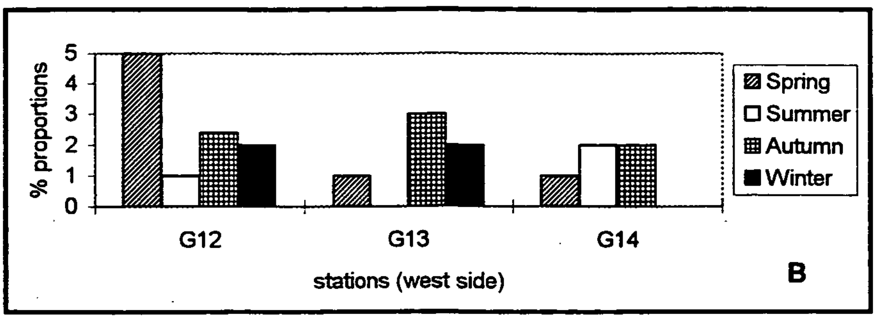


Figure 5.25: Seasonal variation in the proportions of test deformity, Fowey Estuary. a) east side and b) west side.

The deformed species portion of the standing crop total appears to be influenced by species dominance with more instances of test deformation by *H. germanica,* particularly in the summer and less so in the spring. There were more instances of test deformity by *E. williamsoni* in the autumn. As with the other control estuaries there were few occurrences of test deformity by *A. beccarii* in the Fowey Estuary.

***iv*) Avon Estuary**

Seasonally, the highest number of stations with deformed foraminifera were observed in the autumn with the other seasons being equal to each other. The highest proportions of test deformity in the Avon Estuary (Figure 5.26, a and b) were restricted to the upper estuary stations A1 (14%, spring; 16%, autumn) and A2 (29%, summer) and the mid - estuary station A10 (12%, spring). The other upper estuary station A9 on the east side, however, did not exceed 5% deformed tests. Stations A2, A6, A7, A10 and A11 each had only one seasonal sample containing deformed foraminfera but station A4 had deformed tests during the summer, autumn and winter (Figure 5.27, a and b). Station A3 only had deformed foraminifera in summer, winter and spring with the summer value being the highest at 6%. Deformed tests were not observed at any of the stations during every season and none were ever observed at station A5. The average proportions of deformed tests observed on the east and west sides of the estuary ranged between 1% and 5%, and, 0% and 3% respectively. Overall, the proportions of test deformity were less than 3% with the occurrence of zero being common, particularly on the east side in the summer and winter.

The deformed species portion of the total standing crop also appears to be less influenced by species dominance with similar instances of test deformation by

H. germanica and *E. williamsoni* in the summer, spring, winter but less so in the autumn. Instances of test deformity by *A. beccarii* are few and generally appear in the summer and autumn. The deformed proportion of this species is only high on one occasion (e.g., 100% at station A2 in the summer).

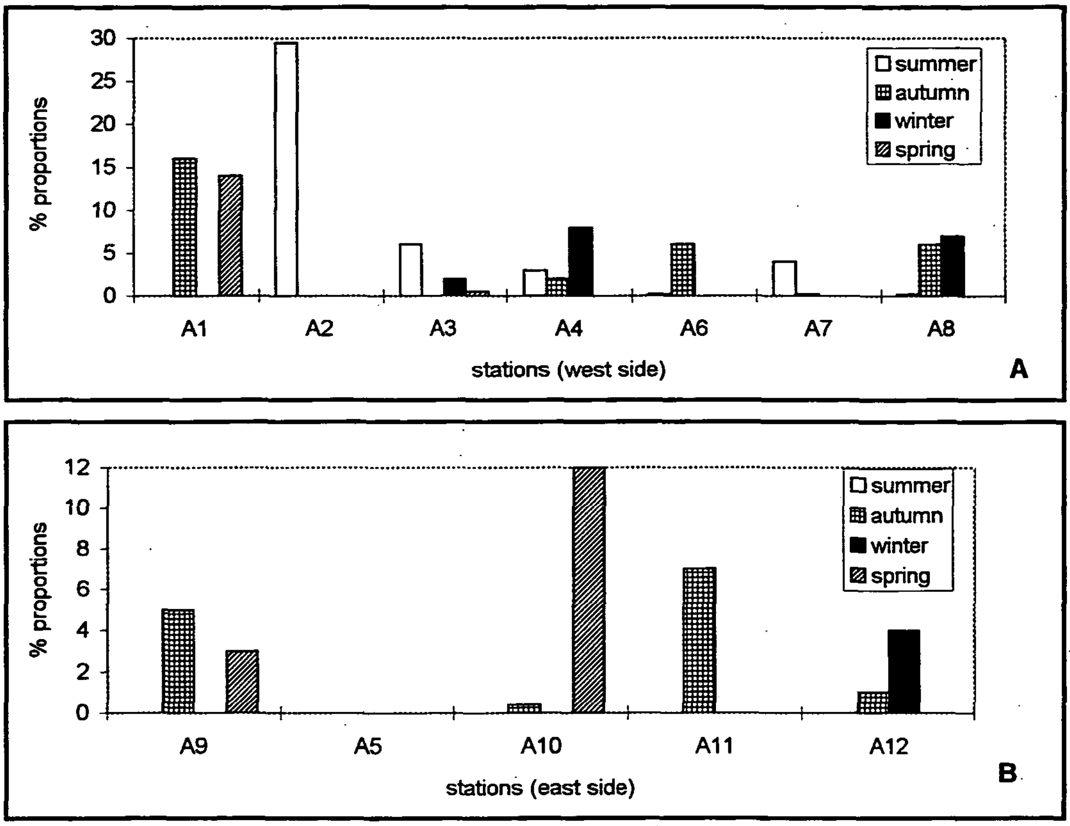


Figure 5.26: Seasonal variation in the proportions of test deformity, Avon Estuary. a) west side and b) east side.

5.8.4 Relationship between deformed tests and other variables

i) Restronguet Creek

With the exception of 1993 (autumn) and 1994 (autumn, winter and spring) the relationship between the proportion of deformed tests and salinity is negative (Table 5.3 [Tables at the end of Chapter Five]). This negative relationship between deformed tests and salinity is only strong for summer 1994, otherwise all other values are significant, as follows, autumn (1992), spring (1993), winter (1994) and summer (1996). The overall negative relationship shown suggests that the proportion of deformed tests decreases down Creek as salinity increases.

Overall, the relationship between temperature and the proportion of deformed tests is negative and on only a few occasions is the correlation significant and at no time were they strong (Table 5.3).

With the exception of spring 1995 (-0.72) there are no strong correlation coefficients shown between organic carbon (%) and the percentages of deformed tests. Data for winter, 1993 and autumn 1995 show a significant relationship between these two parameters. No trend is shown with respect to the level of significance and type of correlation shown (+ or -) for either season or year. With the exception of autumn 1993, there are no significant correlation coefficients shown between the C/N ratio and deformed tests. Again, a trend is not apparent. The relationship between the proportion of deformed tests and each of the three grain size categories is also insignificant (Table 5.4).

Arsenic is the only metal to show a significant relationship with the proportion of deformed tests for the year 1992 (-0.6). With the exception of Pb (1992), all metals for the years 1992 and 1995 show a negative but insignificant relationship with the percentages of deformed tests (Table 5.5, a and d). For 1994, however, all values are positive, with the exception of Ni. Apart from As and Pb, all metals in 1996 showed a positive relationship with the proportion of deformed tests (Table 5.5e).

The reasons for the negative relationship, particularly in 1992 are explored further in Chapter Six. As an initial explanation, however, it would appear that the absence of a standing crop at stations D1, C19 and K20 in 1992 (hence, no deformed foraminifera) would produce a statistical rather than an environmental anomaly. This is supported by the change from all negative values in 1992 (with the exception of Pb) to mostly near neutral positive values in 1994 and 1996 when all stations were colonised by foraminifera. For 1995 all values are negatively, but insignificantly correlated with Al, and Ni approaching neutral. Analysis of metal concentration data from stations D1, C19 and K20 only and the corresponding deformed test data for 1996 (in order to correspond with the laser ablation data, Section 5.9) show Al, Cu, Pb, Ni and Zn to be significantly and positively correlated with the proportion of deformed tests. Copper and Zn show a particularly strong relationship of 0.79 and 0.72 respectively. This data, with the exception of Zn, is similar to the results of the laser analysis (Section 5.9).

***ii*) Erme Estuary**

There are no significant relationships shown between the percentages of deformed tests and the variables of salinity, temperature, organic carbon, the C/N ratio and the three grain size categories (Table 5.6). The exception to this is for temperature (spring) which shows a significant and negative relationship with the proportions of deformed tests (-0.68). There are, also, no significant correlations shown between any metal and the proportion of deformed tests (Table 5.7).

***iii*) Fowey Estuary**

The C/N ratio (-0.54) and Fe (0.53) are the only variables to show a near significant relationship with the proportion of deformed tests (Tables 5.8 and 5.9). All other variables show an insignificant relationship and with respect to metals the values are always positive.

***iv*) Avon Estuary**

Salinity is only significantly correlated with the proportions of deformed tests for spring (-0.6). The percentages of organic carbon show a strong relationship with the proportion of deformed tests for summer (0.78). All other variables, however, show an insignificant relationship with the proportion of deformed tests (Tables 5.10 and 5.11).

5.9 Elemental concentrations within the calcareous tests

The Laser Ablation Inductively Coupled Plasma analysis of calcareous tests (Plates 14 and 15) detected only low concentrations of the metals Cr, As and Cd and the majority of values were beyond detection limits; these data are not given here.

Metal and test form	Mean	Minimum	Maximum	Median
Al deformed	2.97	1.0	4.57	3.15
Al undefomed	1.34	0.9	1.97	1.23
Cu ^{63} deformed	0.8	0.47	1.23	0.74
Cu ^{63} undeformed	0.5	0.47	0.57	0.53
Cu ^{65} deformed	0.8	0.42	1.3	0.72
Cu ^{65} undeformed	0.53	0.48	0.57	0.53
Fe deformed	5.8	3.9	7.7	5.84
Fe undeformed	3.75	2.83	5.0	3.58
Ni deformed	0.39	0.12	0.98	0.22
Ni undeformed	0.16	0.15	0.17	0.16
Pb deformed	0.056	0.033	0.1	0.045
Pb undeformed	0.019	0.016	0.023	0.019
Zn ^{64} deformed	1.16	0.68	1.6	1.18
Zn ^{64} undeformed	1.15	0.78	1.57	1.12
Zn ^{66} deformed	1.1	0.63	1.6	1.15
Zn ^{66} undeformed	1.23	0.94	1.8	1.1

Table 5.12: Elemental concentrations within the tests of deformed and undeformed specimens. The values are in units of concentration and the two isotopes of Cu and Zn are included as shown (Stubbles and Chenery, in prep.).

In the deformed tests, the metals Al, Cu, Fe, Ni and Pb were greater (Table 5.12) than in the undeformed tests as mean, maximum and median values but the minimum values for Al, Cu and Ni were very similar which suggests background levels for each element (Stubbles and Chenery, in prep.). In the case of Zn, however, the difference in concentration between the deformed and undeformed specimens was insignificant. The order of metal concentration in deformed and undeformed tests is the same, as follows, Fe>Al>Zn>Cu>Ni>Pb. This is similar to the sediment metal concentrations (Fe>Zn>Al>Cu>As>Pb>Ni) with the exception of Al and Ni which are placed higher (Chapter Four, Section 4.7.4). The values given for each isotope were very similar as would be expected for correct quantitation (S. Chenery, pers.comm.).

Correlation coefficient analysis carried out between the foraminiferal laser analysis and the sediment geochemical data (Table 5.13) produced strong positive associations (>0.7) for the metals Cu, Ni and Pb, with the latter two approaching unity. There were strong negative associations between the undeformed tests and sediment concentrations of Al and Cu (as the isotope 65 but not 63). Overall, therefore, the results obtained for the deformed tests were positive, but were negative with respect to the undeformed tests.

foraminiferal tests and metals	Correlation coefficient
Al/D - Al	0.4
Al/U - Al	**-0.77***
Cu^{63}/D - Cu	**0.77***
Cu^{63}/U - Cu	-0.06
Cu^{65}/D - Cu	**0.81***
Cu^{65}/U - Cu	**-0.83***
Fe/D - Fe	0.42
Fe/U - Fe	-0.27
Ni/D - Ni	**0.94***
Ni/U - Ni	-0.42
Pb/D - Pb	**0.996+**
Pb/U - Pb	-0.3
Zn^{64}/D - Zn	0.2
Zn^{64}/U - Zn	-0.06
Zn^{66}/D - Zn	0.08
Zn^{66}/U - Zn	-0.26

Table 5.13: Statistical relationship between metal concentrations in the foraminiferal tests and in the sediment. Strong values are in bold (D = deformed and U = undeformed). Values marked * have a 95% confidence limit and + with 99% (C.L.).

Plate 14

Figure 1. *Haynesina germanica* (deformed), Restronguet Creek, station D1, summer 1995, showing two craters created by laser ablation.

Figure 2. Enlargement of the above two craters in Figure 1, in the final and penultimate chambers. The crater marked a is a more regular shape than crater b.

Figure 3. Crater a showing even ablation.

Figure 4. Crater b showing uneven ablation.

Figure 5. *Haynesina germanica* (undeformed), Restronguet Creek, station D1, summer 1995, with a laser ablation crater in one of the earlier formed chambers.

Figure 6. Enlargement of the crater in Figure 5.

Plate 14

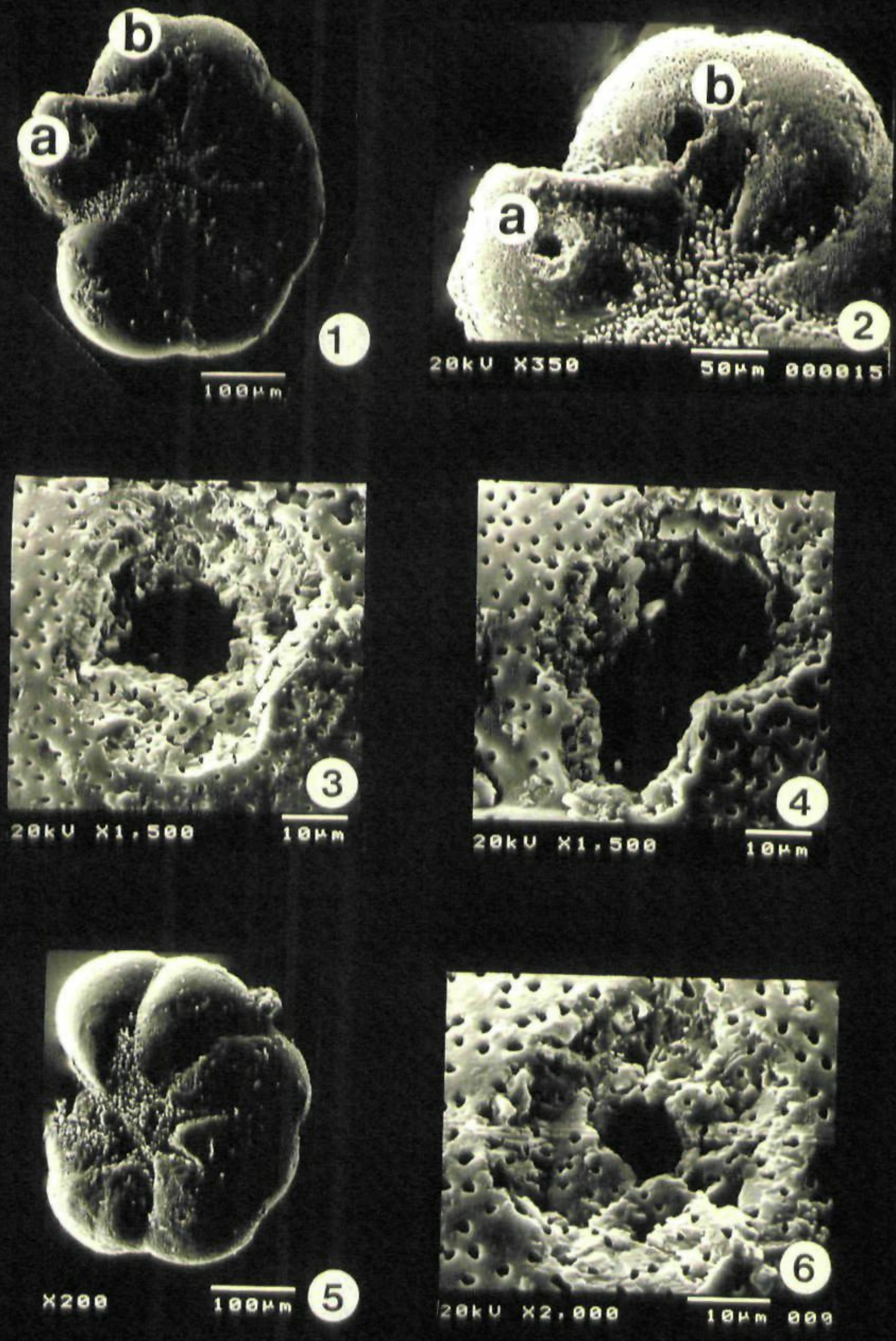

b
a
1
100µm
b
a
2
20kV X350
50µm 000015
3
20kV X1,500
10µm
4
20kV X1,500
10µm
X200
100µm
5
6
20kV X2,000
10µm 009

Plate 15

Figure 1. *Ammonia beccarii*, umbilical side, Restronguet Creek, station C19, summer 1995. Laser ablation of two chambers, crater marked 2 is unusually smooth.

Figure 2. *Ammonia beccarii*, spiral side, Restronguet Creek, station C19, summer 1995. Irregular shaped crater.

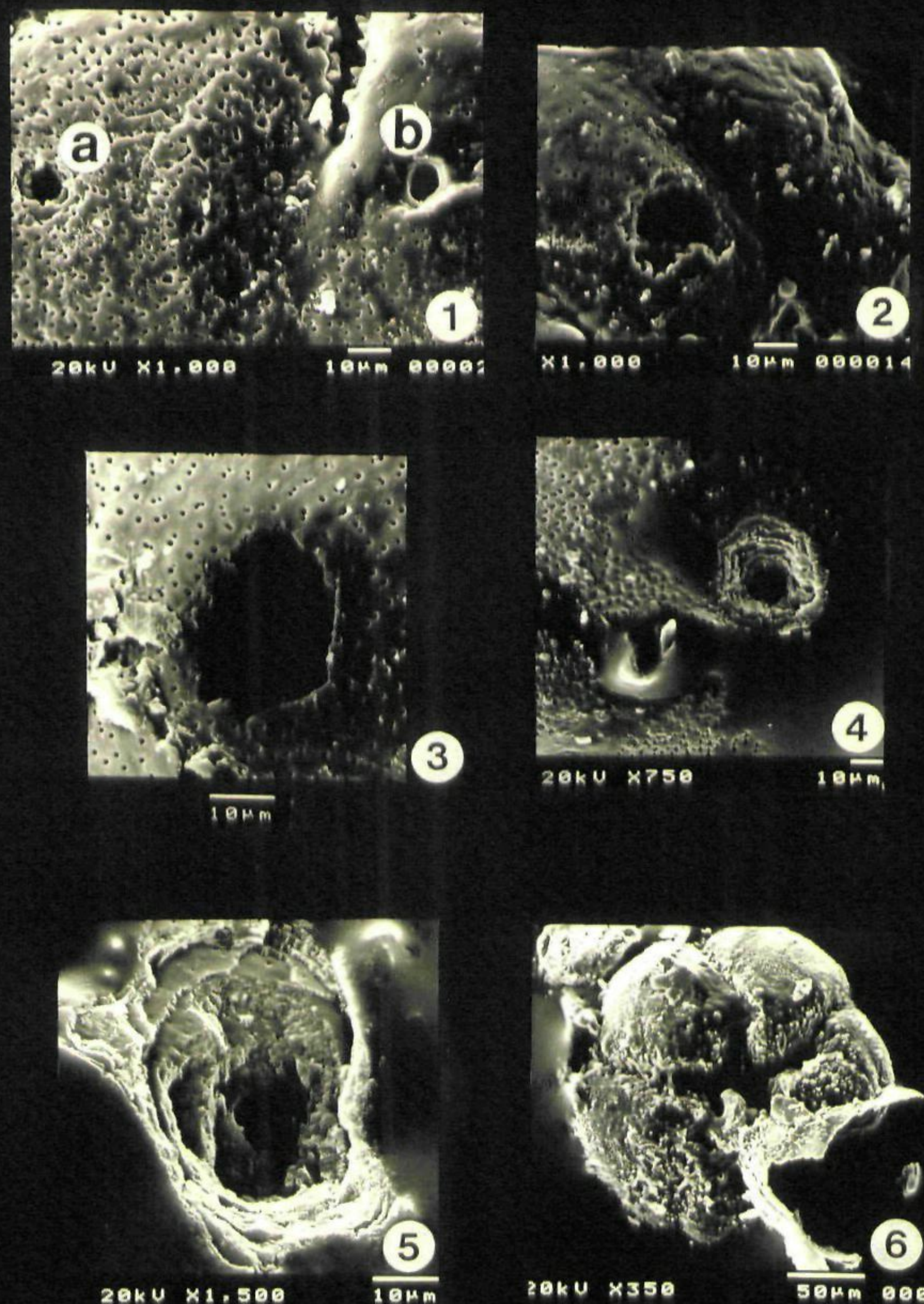
Figure 3. *Ammonia beccarii*, spiral side, Restronguet Creek, station C19, summer 1995. Crater exposing thinned wall.

Figure 4. *Ammonia beccarii*, spiral side, Restronguet Creek, station C19, summer 1995. Laser ablation went through the resin fixative first (hence the smooth surface to the right of the test). The crater itself approximates to a flat bottomed cone and exposes several layers of calcareous growth.

Figure 5. Laser ablation through resin. Again the exposed test wall shows several layers of calcareous growth.

Figure 6. *Ammonia beccarii*, umbilical side, deformed, Restronguet Creek, station K20, summer 1995. An example of complete chamber loss. The chamber (bottom right of the picture) has almost been entirely ablated away.

Plate 15



a
b
1
20kV X1,000
10μm 00001
2
X1,000
10μm 000014
3
10μm
4
20kV X750
10μm
5
20kV X1,500
10μm
6
20kV X350
50μm 00

5.10. Acid etching of calcareous tests

In Restronguet Creek, acid etching of living individuals of the three calcareous species, *Haynesina germanica, Elphidium williamsoni* and *Ammonia beccarii* produced a white, opaque finish to these normally glassy hyaline tests (Figure 5.27, a and b). Acid attack also caused weakening, premature breakage, test loss and the rose Bengal stain which is usually visible, was obscured so that the tests resembled dead foraminifera (Murray and Wright, 1970; Stubbles, *et al.*, 1996a, b). Acid corrosion of the tests also produced test wall layering, thinning and a chalky internal structure (Stubbles, *et al.*, 1996b). In addition to full test opacity, the less damaging effect of partial opacity was also evident which produced a slightly dulled surface, but through which the rose Bengal stain was visible.

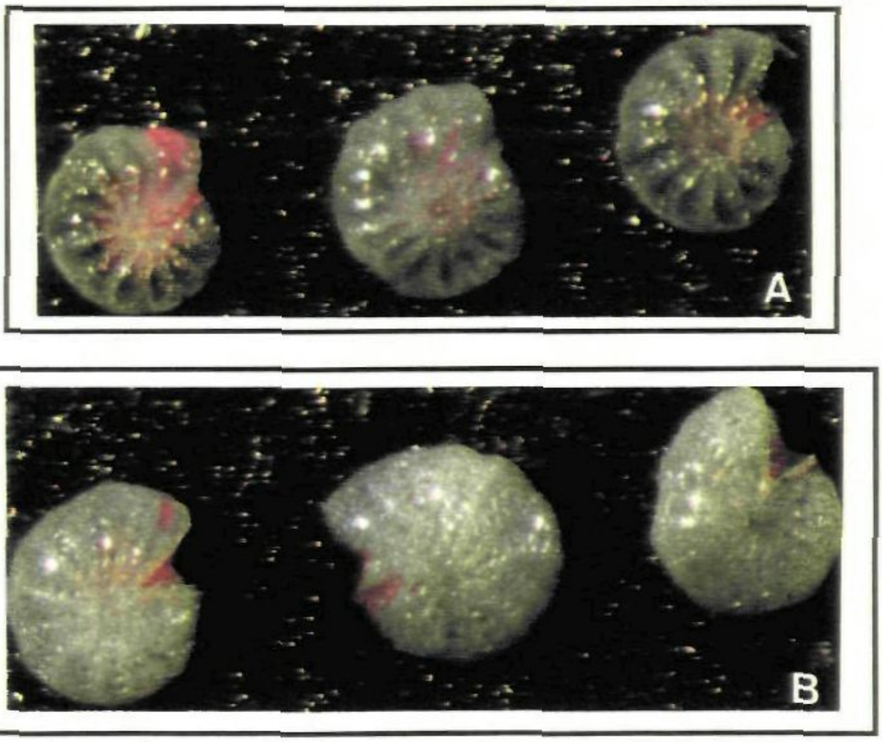


Figure 5.27: Tests of *E. williamsoni,* a) hyaline and b) opaque.

The spatial distribution in the occurrence of full opaque tests was between stations D1 and P10 on the north side of Restronguet Creek and C19 and H23 on the south side (by the time colonisation had begun at station K20 in autumn 1994 the occurrence of full test opacity was no longer a feature). At stations TW27 - PI30, and, PC13 and CY16 partial opacity was evident but without premature damage. Partial opacity occurred at these stations between 1992 and 1996, with the exception of winter 1993 when fully opacity appeared in 100% of the stained assemblage, at all stations and this coincided with a rise in river water acidity (pH 4.4) entering the Creek (Chapter Four, Figure 4.18). Seasonally, the winter had the highest and most frequent occurrence of full opaque tests at stations D1 - P10 in 1993 and 1994. In winter 1995 only stations D1 and TC6 had tests which showed full opacity. Overall, therefore, the proportion of full opaque tests and the Creek area affected has diminished with time and by the summer of 1994 there were no opaque tests, when formerly these had been 100% of the live assemblage at the upper and mid - Creek stations, on both sides of the Creek.

5.11 Loss of calcareous tests through acid dissolution

5.11.1 Introduction

The dead assemblage comprises empty tests belonging to the indigenous species and those transported in from adjacent environments. As a consequence of this mixing, the dead assemblage can be dissimilar to the live assemblage, particularly in estuaries which contain low diversity assemblages (Murray, 1984; 1991; Wang and Murray, 1983). An accumulation of agglutinated species in the dead assemblage relative to the stained assemblage may be indicative of calcareous test dissolution (Alve and Murray, 1995a; Murray, 1970a). The accumulation and removal of these tests is dependent upon a number of postmortem influences (e.g., test size and shape [Murray, 1986; Snyder *et al.* 1990], dredging, wave and tidal energy [Murray *et al.*, 1982], estuarine orientation and dissolution [Boltovoskoy and Totah, 1992]) and it is difficult to make comparisons between estuaries. Only general comparisons have, therefore, been made here between each estuary included in this study.

The technique used by Murray (1989; 1991) requires the presence of agglutinated species to determine calcareous test loss but as these species are absent in Restronguet Creek the increase in the percentage proportions of the non - indigenous species have been used instead to determine relative rates of calcareous test dissolution as an indicator of the changes in the volume of acidified water entering the Creek since 1992 (Chapter Four, Section 4.5).

5.11.2 Distribution of the transported-in calcareous tests

***i*) Restronguet Creek**

The only direct indication of test dissolution is from the short cores taken from Restronguet Creek. The abundance of foraminifera (indigenous and transported - in) decreased down each core and, in core TC6 (core length 50cm) they disappeared below 15cm (Stubbles *et al.*, 1996b) but were present throughout cores TC9 (core length 40cm) and TW27 (core length 30cm).

Between autumn 1992 and autumn 1993 surface samples taken from the upper and mid - Creek stations, in the majority of examples, had no transported-in species with the average proportions being very low. As a consequence, the diversity and species proportions of the live and dead assemblages were very similar. The other stations had low proportions (<1%) of transported - in species and again the dead assemblage closely resembled that of the living. By the autumn of 1995, however, the sediments at most stations had transported - in species >2% and every seasonal sample mean has shown a proportional increase (Figure 5.28). The average proportions of transported - in tests in 1996 was 8% in the autumn, 9% in winter, 9.3% in the spring and 3% in the summer. The autumn and spring data, for example, show the smoothest trend with a gradual increase between 1992/93 and 1994 which may indicate a lack of disturbance due to storm events which can cause unusual rates of accumulation in transported - in species, or conversely, the absence of a major acid mine water discharge which is accompanied by a steady increase in the pH of the pore water and channel water. The greatest increase was shown by the winter data sets in 1995 and 1996 (Figure 5.28) reflecting the sustained rise and stability in pH levels (>6.5). The summer samples usually had the smallest proportions of transported - in species every year (Stubbles *et al.*, 1996b). The average summer values varied little between 1993 and 1995 (2% each year) but in 1996 there was an increase of 1% so that of the seasons, the summer produced the smallest increase with time. This may be due to relatively lower tidal energy (fewer storm events occur in the summer) and the reduced amount of acidified mine water being discharged from the abandoned mines during the summer, thus leading to channel water of a higher pH. These assumptions are supported by the rainfall and pH data given in Chapter Four (Figure 4.18).

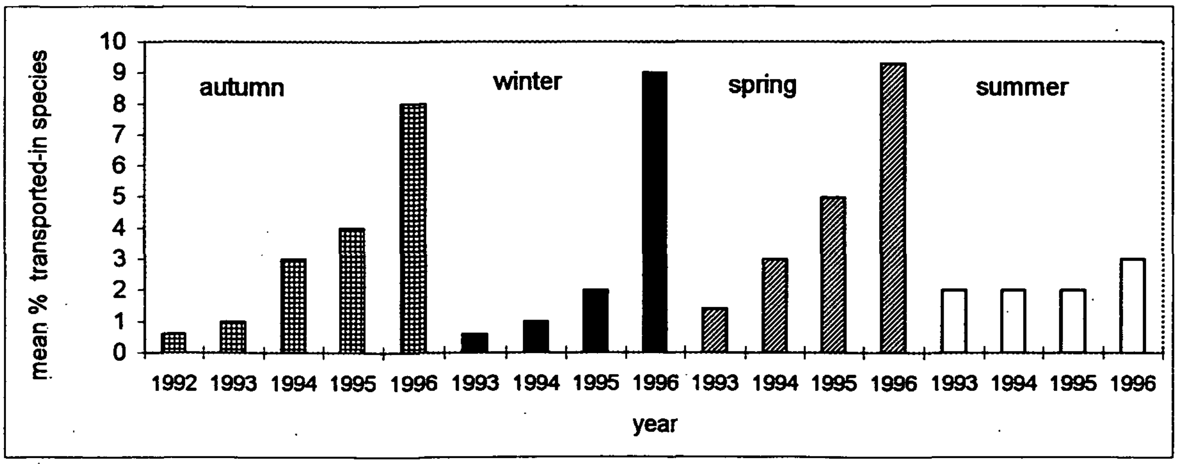


Figure 5.28: Seasonal proportions of transported-in species, Restronguet Creek.

Spatially, there was a trend throughout the period of sampling, with the highest proportions generally appearing at the lower Creek stations CY16 and PI30, and least at the upper Creek stations, for example, D1 and C19. This sorting process is apparent in all the estuaries and is probably associated with a decrease in tidal energy (Wang and Murray, 1983). In Restronguet Creek, however, there is the additional influence of acid dissolution which may explain the exceptionally low proportions. The greatest abundance of transported - in species, after 1995, appeared in the $\geq$63µm size fraction and least in the $\geq$250µm size fraction. Prior to 1995 differential test size distribution was less apparent, which suggests that transportation was not a major modifying influence but may have been after 1995.

Species abundance and the diversity of the dead assemblage has changed over time and in addition to the first appearance of *Quinqueloculina dimidata* and *Elphidium macellum*, more species have been observed (Chapter Three, Table 3.1). In the majority of cases the transported - in species were the most robust forms and, those of a surface attached habit (e.g., *Glabratella milletti* and *Gavelinopsis praegeri*). The shallow infaunal species with thinner tests belonging, for example, to the genus *Lagena*, were particularly rare. The proportions of transported - in agglutinated species (e.g., *Trochammina ochracea*) remained fairly static between 1992 and 1996. The agglutinated indigenous species which commonly colonise the control estuaries (Section 5.4, *ii - iv*) were consistently absent in the dead assemblage, which supports the assumption that they do not colonise the area (Carrick Roads) adjacent to Retronguet Creek. Testate amoebae, originating from terrestrial habitats were occasionally found in samples taken throughout the Creek with the onset of sampling (Chapter Three, Table 3.1), although their occurrence has always been low. The most common species was *Centropyxis aculeata* and occasionally individuals were observed to be stained.

ii) **The Erme and Avon Estuaries**

The cores taken from the Erme stations E6 and E8 had a greater abundance of calcareous tests compared with those taken from Restronguet Creek, but similarly the abundance diminished with increasing depth. With respect to the proportions of transported - in species, the Erme and Avon data had similar proportions ($\leq$58% and $\leq$65% respectively) and the distribution patterns were closely similar. The combined sample means were, however, higher in the Avon relative to the Erme for the autumn, winter and spring and this may reflect localised accumulation points or periodic storm events (but as these estuaries were not sampled concurrently it is impossible to identify a factor accountable for this anomaly). Upwards of 70 species were introduced but the proportions of each was low (<1%), with the exception of *Cibicides lobatulus* (the most common species transported - in) which accounted for approximately 40% of the dead assemblage at the stations in the lower estuary (Stubbles *et al.*, 1996b). The high production rates and attachment habit of this species may account for this high level of incursion in the lower estuary areas. Other common calcareous species (between 2% and 6% of all transported - in species) were *Asterigerinata mamilla* and *Rosalina anomala*. At the genus level the species of *Quinquloculina*, *Guttulina* and *Lagena* were also frequently found. There were also rare occurrences of planktonic species; e.g., *Globigerina bulloides*. The commonest agglutinated species were *Haplophragmoides wilberti*, *Trochammina ochracea* and *Reophax moniliformis* some of which were stained red. As a consequence of the high abundance of transported - in species in each estuary, the living and dead assemblages were dissimilar, particularly in the lower estuary stations S20 (Erme) and A12 (Avon) which are closest to the source of these marine species and had the highest proportions (Murray, 1970; Stubbles *et al.*, 1996b). Again, higher abundances of these transported - in species occurred in the finer fractions ($\geq$63µm - $\leq$125µm size fraction) which suggests transportation in suspension (Wang and Murray, 1983). Testate amoebae routinely appeared in samples from both these estuaries (Chapter Three, Table 3.1) but there were no commonly occurring species.

***iii*) The Fowey Estuary**

The Fowey Estuary had fewer transported - in species and the proportions did not exceed 15% of the dead assemblage. The continental shelf species *T. ochracea*, *Eggerelloides scabra*, *H. wilberti*, *R. moniliformis*, *Quinqueloculina dimidata* and *Q. lata* commonly appeared but not in every sample and individually did not exceed 1%. The lower, main channel stations had the highest proportions of transported - in species and greatest diversity from a maximum of 50 different species transported - in. Overall, the upper estuary and subsidiary creek stations had proportions below 5% and the lower estuary stations up to 15% in the winter but in the majority of cases were below 10%. The daily dredging of the lower estuary (Chapter One, Section 1.6, *iii*) may account for the low abundance of introduced species throughout, or, the slightly acidic pore water conditions removing calcareous tests by dissolution (Chapter Four, Section 4.5). The short core taken in the upper estuary shows that the proportions of these introduced species has historically changed and between the 33cm level and the base of the core (40cm), a period which pre-dates dredging (1904), their abundance was greater than after this time. Testate amoebae were found in samples taken from the subsidiary creek stations LPO3, RC4 and PPH11 but not in the main channel samples and relative to the Erme and Avon there were fewer species present.

Variable	‰				°C				C%				C/N			
1992	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**
S.crop	*0.64*				0.24				0.26				0.14			
H. germanica	0.17				0.05				0.06				0.3			
E. williamsoni	0.21				0.35				0.07				0.3			
A. beccarii	0.51				0.3				0.2				0.2			
% deformed	*-0.59*				0.13				0.4				0.34			
1993	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**
S.crop	*0.68*	0.3	**0.79**	**0.72**	0.32	0.26	0.4	**0.74**	0.24	-0.3	0.2	-0.15	-0.3	-0.2	0.1	0.02
H. germanica	0.18	0.42	0.37	0.37	0.1	0.44	-0.1	0.48	-0.24	0.12	0.03	0.11	-0.3	-0.2	-0.1	0.1
E. williamsoni	-0.04	*0.56*	0.19	0.2	0.32	0.37	0.3	0.2	-0.04	-0.11	-0.01	-0.03	-0.1	-0.1	-0.3	0.15
A. beccarii	0.34	*0.61*	0.1	0.1	-0.34	*0.67*	-0.1	0.2	-0.06	-0.04	-0.05	-0.04	-0.2	-0.1	-0.2	-0.15
% deformed	0.35	*-0.5*	*-0.6*	-0.36	-0.04	-0.3	-0.4	-0.34	-0.37	*-0.63*	-0.36	-0.2	-0.01	-0.39	-0.1	0.3
1994	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**
S.crop	0.13	*0.66*	**0.71**	**0.84**	-0.36	**0.75**	0.28	**0.8**	-0.41	0.35	0.32	0.4	-0.43	-0.1	0.01	0.03
H. germanica	0.25	0.26	**0.7**	0.01	0.17	0.33	0.2	0.18	*0.62*	0.25	0.26	-0.1	-0.1	0.01	0.01	0.1
E. williamsoni	-0.36	**0.84**	*0.4*	*0.59*	-0.2	*0.65*	-0.1	*0.55*	*-0.64*	0.31	0.43	0.18	0.1	0.13	-0.15	0.25
A. beccarii	0.5	*0.69*	**0.74**	*0.6*	0.19	0.38	0.4	0.48	0.24	0.12	0.03	-0.06	-0.2	0.04	0.05	-0.12
% deformed	0.33	*0.55*	0.31	**-0.77**	*0.56*	0.45	0.3	*-0.68*	-0.1	0.17	0.15	0.001	*-0.6*	-0.14	-0.26	0.23
1995	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**
S.crop	*0.69*	0.53	**0.81**	*0.66*	*0.5*	0.57	0.23	0.52	0.38	-0.21	0.36	0.15	0.5	-0.5	-0.3	0.15
H. germanica	0.23	*0.58*	0.52	0.40	-0.48	*0.57*	0.45	0.47	0.03	0.16	0.46	-0.34	-0.5	0.04	-0.12	0.01
E. williamsoni	**-0.71**	**0.78**	-0.35	-0.43	0.07	0.13	-0.45	*-0.55*	-0.5	-0.1	-0.15	-0.27	-0.01	0.1	-0.03	0.1
A. beccarii	*0.63*	0.36	0.34	0.2	0.13	0.5	0.13	0.17	0.5	0.4	0.32	0.43	0.45	-0.2	0.4	-0.15
% deformed	-0.14	-0.44	-0.17	-0.4	0.24	*-0.54*	0.2	-0.34	*-0.55*	0.02	-0.72	-0.1	-0.01	0.32	-0.36	-0.11
1996	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**
S.crop	0.17	*0.59*	*0.59*	*0.61*	0.02	*0.64*	0.2	*0.68*	*-0.64*	-0.12	-0.03	*0.62*	-0.3	0.04	-0.4	0.12
H. germanica	0.34	-0.44	-0.2	*-0.69*	0.005	-0.26	0.19	**-0.78**	*0.58*	0.05	-0.02	-0.06	-0.2	**-0.9**	0.23	0.03
E. williamsoni	-0.45	0.29	-0.2	0.46	0.02	0.11	-0.12	0.51	*-0.55*	*-0.6*	0.33	-0.07	0.3	0.4	0.45	-0.04
A. beccarii	*0.57*	0.1	0.3	*0.66*	-0.04	0.08	-0.1	*0.65*	0.24	0.4	-0.15	0.32	-0.3	0.4	-0.5	0.01
% deformed	-0.39	0.31	-0.1	*-0.63*	-0.05	0.18	-0.1	*-0.62*	-0.12	-0.02	0.003	-0.23	0.4	-0.34	0.19	0.06

Table 5.3: Restronguet Creek. Statistical relationship between the variables The shaded areas denote no data collection. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	Sediment Grain Size		
Variable	**≤16µm**	**>16µm - <63µm**	**≥63µm**
S.crop	-0.32	0.1	0.17
H. germanica	-0.29	-0.1	0.23
E. williamsoni	0.32	0.1	-0.17
A. beccarii	0.1	-0.1	-0.03
% deformed	0.47	0.19	-0.34

Table 5.4: Restronguet Creek. Statistical relationship between the variables: standing crop,percentage proportions of species and deformed tests and the sediment grain size categories. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	METALS 1992						
Variable	**Al**	**Fe**	**Cu**	**Pb**	**As**	**Ni**	**Zn**
S.crop	-0.09	0.25	-0.08	0.36	0.11	-0.22	-0.18
H. germanica	-0.36	-0.47	-0.3	0.15	-0.22	0.08	-0.27
E. williamsoni	*-0.66*	*-0.55*	*-0.55*	0.004	-0.54	-0.38	*-0.67*
A. beccarii	-0.28	-0.04	-0.15	0.41	-0.13	-0.29	-0.31
% deformed	-0.46	-0.41	-0.37	0.03	*-0.6*	-0.2	-0.44

Table 5.5a: Restronguet Creek. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for 1992. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	METALS 1993						
Variable	**Al**	**Fe**	**Cu**	**Pb**	**As**	**Ni**	**Zn**
S.crop	0.15	0.48	0.06	0.06	0.46	0.22	0.15
H. germanica	-0.3	-0.06	0.07	-0.11	0.08	-0.16	0.11
E. williamsoni	-0.29	-0.07	-0.37	-0.01	0.15	-0.17	-0.31
A. beccarii	0.23	0.31	0.16	0.08	0.22	0.19	0.19
% deformed	0.24	-0.46	-0.1	-0.1	-0.001	-0.28	-0.1

Table 5.5b: Restronguet Creek. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for 1993. Values which are enboldened are considered to be strongly correlated ($\geq$0.7) and values shown in italics are significant ($\geq$0.55 - $\leq$0.69).

	Metals 1994						
Variable	**Al**	**Fe**	**Cu**	**Pb**	**As**	**Ni**	**Zn**
S.crop	-0.09	-0.13	0.13	-0.06	-0.27	-0.08	0.08
H. germanica	*0.68*	*0.66*	*0.64*	**0.71**	0.34	*0.58*	*0.65*
E. williamsoni	*-0.69*	*-0.69*	*-0.65*	**-0.75**	-0.36	*-0.56*	*-0.64*
A. beccarii	0.38	0.46	0.38	*0.5*	0.24	0.21	0.32
% deformed	0.03	0.08	0.04	0.16	0.19	-0.1	0.1

Table 5.5c: Restronguet Creek. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for 1994. Values which are enboldened are considered to be strongly correlated ($\geq$0.7) and values shown in italics are significant ($\geq$0.55 - $\leq$0.69).

	Metals 1995						
Variable	**Al**	**Fe**	**Cu**	**Pb**	**As**	**Ni**	**Zn**
S.crop	*-0.56*	-0.2	*-0.64*	-0.39	-0.25	-0.29	*-0.62*
H. germanica	0.35	0.3	0.42	0.35	0.14	0.4	0.42
E. williamsoni	0.31	-0.06	0.32	0.31	-0.06	0.18	0.28
A. beccarii	-0.47	-0.06	-0.5	-0.48	0.005	-0.36	-0.46
% deformed	-0.16	-0.36	-0.23	-0.24	-0.26	-0.02	-0.27

Table 5.5d: Restronguet Creek. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for 1995. Values which are enboldened are considered to be strongly correlated ($\geq$0.7) and values shown in italics are significant ($\geq$0.55 - $\leq$0.69).

	Metals 1996						
Variable	**Al**	**Fe**	**Cu**	**Pb**	**As**	**Ni**	**Zn**
S.crop	-0.44	-0.45	-0.33	-0.48	-0.41	-0.41	-0.41
H. germanica	-0.24	-0.13	-0.33	0.04	-0.08	-0.23	-0.27
E. williamsoni	0.38	0.23	0.48	-0.01	0.13	0.4	0.43
A. beccarii	*-0.58*	-0.4	*-0.67*	-0.05	-0.19	*-0.66*	*-0.64*
% deformed	0.14	0.02	0.21	-0.2	-0.23	0.07	0.13

Table 5.5e: Restronguet Creek. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for 1996. Values which are enboldened are considered to be strongly correlated ($\geq$0.7) and values shown in italics are significant ($\geq$0.55 - $\leq$0.69).

Variable	**‰**				**°C**				**C%**				**C/N**				**Sediment Grain Size**		
Season	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**≤16µm**	**>16-63µm**	**≥63µm**
S.crop	-0.2	0.32	0.3	0.46	-0.06	0.1	0.42	0.33	0.31	0.2	0.3	-0.13	0.1	0.16	0.15	-0.3	-0.09	-0.09	0.12
H. germanica	*0.5*	*0.68*	*0.67*	*0.63*	0.004	*0.64*	0.5	*0.68*	-0.17	-0.41	-0.45	-0.04	0.06	-0.4	-0.4	-0.24	0.32	-0.1	-0.02
E. williamsoni	*0.66*	**0.83**	**0.75**	*0.68*	0.37	**0.82**	0.52	*0.5*	0.14	-0.18	0.15	-0.08	-0.002	-0.18	-0.24	-0.13	-0.22	-0.22	0.28
A. beccarii	0.18	-0.14	-0.02	0.33	0.03	-0.04	-0.27	0.35	0.21	-0.28	-0.21	0.27	-0.01	-0.1	-0.1	-0.1	0.62	0.18	-0.39
M. fusca	**-0.84**	-0.24	*-0.56*	0.02	-0.33	-0.27	-0.33	-0.3	-0.02	0.001	0.26	0.37	0.005	0.22	0.42	**0.77**	-0.47	*-0.53*	-0.03
J. macrescens	-0.46	0.13	-	0.12	-0.11	0.51	-	0.2	-0.11	-0.23	-	0.15	-0.33	-0.04	-	0.2	-0.1	0.04	-0.1
T. inflata	-0.03	-	-	0.01	-0.1	-	-	-0.14	0.25	-	-	-0.13	0.27	-	-	0.46	-0.39	-0.1	-0.3
% deformed	0.49	-0.37	-0.43	-0.37	0.15	0.1	*-0.68*	-0.3	-0.1	0.2	-0.12	0.35	0.06	0.2	0.29	0.05	0.43	0.19	-0.3

Table 5.6: The Erme Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and the environmental variables: salinity, temperature, percentage carbon, C/N ratio and sediment grain size. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	Metals					
Variable	**Al**	**Fe**	**Cu**	**Pb**	**Ni**	**Zn**
S.crop	0.16	0.01	0.08	0.07	-0.04	0.07
H. germanica	-0.2	0.18	0.003	-0.25	0.28	-0.19
E. williamsoni	-0.18	-0.08	-0.05	-0.2	0.07	-0.33
A. beccarii	-0.21	-0.14	-0.2	-0.16	-0.11	-0.2
M. fusca	0.33	0.02	0.02	0.37	-0.18	0.46
% deformed	0.03	-0.05	-0.15	-0.12	-0.09	0.28

Table 5.7: Erme Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for autumn 1993. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

Variable	‰				°C				C%				C/N				Sediment Grain Size		
Season	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**A**	**W**	**SP**	**S**	**≤16μm**	**>16-63μm**	**≥63μm**
S.crop	0.35	0.14	*0.57*	0.52	0.43	-0.1	**0.83**	**0.87**	-0.42	-0.31	0.15	-0.34	-0.3	-0.15	-0.3	0.04	-0.47	0.33	-0.14
H. germanica	*0.62*	-0.02	**0.77**	-0.25	0.44	0.22	**0.7**	-0.28	-0.29	*-0.58*	0.2	-0.39	-0.003	-0.4	-0.15	0.12	-0.32	-0.09	0.27
E. williamsoni	0.14	*0.57*	0.1	*0.59*	0.47	*0.57*	-0.29	*0.65*	-0.5	-0.14	0.34	0.17	-0.5	-0.15	0.39	-0.11	0.03	-0.12	0.09
A. beccarii	0.52	*0.67*	0.4	0.54	0.54	*0.58*	0.34	*0.56*	-0.36	0.01	-0.08	-0.18	-0.23	0.26	*-0.68*	0.25	-0.41	0.31	-0.14
M. fusca	**-0.71**	*-0.62*	**-0.79**	-0.5	*-0.68*	**-0.74**	*-0.62*	*-0.58*	*0.55*	0.47	-0.27	0.36	0.43	0.31	0.1	0.1	-0.35	-0.3	-0.18
J. macrescens	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
T. inflata	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
% deformed	0.19	0.17	0.34	-0.15	-0.18	0.27	0.23	-0.1	-0.26	0.08	-0.23	-0.15	-0.02	0.29	-0.36	*-0.54*	0.06	0.08	-0.08

Table 5.8: The Fowey Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and the environmental variables: salinity, temperature, percentage carbon, C/N ratio and sediment grain size. Values which are enboldened are considered to be strongly correlated(≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	Metals					
Variable	**Al**	**Fe**	**Cu**	**Pb**	**Ni**	**Zn**
S.crop	-0.35	-0.32	-0.5	-0.1	-0.3	*-0.55*
H. germanica	0.13	0.03	0.22	0.39	0.17	0.29
E. williamsoni	0.37	0.27	0.17	0.31	0.14	0.1
A. beccarii	-0.27	-0.33	-0.11	0.1	-0.1	-0.17
M. fusca	-0.3	0.18	0.24	-0.46	-0.22	-0.2
% deformed	0.47	*0.53*	0.23	0.39	0.32	0.16

Table 5.9: Fowey Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for autumn 1994. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

Variable	‰				°C				C%				C/N				Sediment Grain Size		
Season	A	W	SP	S	A	W	SP	S	A	W	SP	S	A	W	SP	S	≤16µm	>16-63µm	≥63µm
S.crop	0.24	0.53	0.1	0.33	0.04	0.43	0.07	0.44	-0.11	-0.22	0.23	0.12	-0.1	0.4	0.5	0.15	0.13	**0.73**	-0.33
H. germanica	-0.26	*0.59*	*0.59*	**0.7**	0.23	0.38	*0.67*	*0.62*	-0.13	-0.04	0.16	0.16	0.18	0.1	0.37	-0.23	0.17	0.45	0.01
E. williamsoni	0.26	*0.58*	0.13	**0.76**	0.35	0.5	0.26	**0.81**	0.1	0.38	*0.5*	-0.19	-0.26	*0.6*	0.13	0.39	-0.4	0.02	0.38
A. beccarii	0.06	0.17	-0.1	-0.02	0.02	-0.02	-0.17	0.17	-0.18	-0.08	0.25	0.48	0.2	0.01	*0.6*	0.18	*0.6*	0.43	-0.34
M. fusca	0.37	*-0.65*	-0.29	**-0.78**	0.22	*-0.55*	-0.4	**-0.84**	0.08	-0.4	-0.46	-0.02	0.2	**-0.7**	-0.4	-0.23	0.19	-0.27	0.31
J. macrescens	0.49	0.43	0.03	-0.21	0.28	0.39	0.19	-0.26	-0.34	*0.66*	-0.19	-0.01	*0.5*	**0.76**	-	-0.5	0.06	0.31	-0.16
T. inflata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
% deformed	-0.48	0.16	*-0.6*	0.01	-0.19	0.1	-0.36	-0.37	-0.22	0.48	-0.18	**0.78**	-0.16	0.16	-0.04	0.23	0.47	0.15	-0.15

Table 5.10: The Avon Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and the environmental variables: salinity, temperature, percentage carbon, C/N ratio and sediment grain size. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

	Metals					
Variable	Al	Fe	Cu	Pb	Ni	Zn
S.crop	0.05	0.27	*0.65*	0.41	-0.28	*0.61*
H. germanica	-0.39	-0.39	-0.11	-0.1	-0.48	-0.14
E. williamsoni	0.47	0.34	0.27	-0.15	0.5	0.33
A. beccarii	-0.53	-0.42	0.0007	-0.18	**-0.85**	-0.06
M. fusca	-0.1	-0.03	-0.31	0.3	-0.13	-0.32
% deformed	-0.17	0.07	-0.2	0.05	0.24	-0.21

Table 5.11: Avon Estuary. Statistical relationship between the variables: standing crop, percentage proportions of species and deformed tests and metal concentrations for autumn 1995. Values which are enboldened are considered to be strongly correlated (≥0.7) and values shown in italics are significant (≥0.55 - ≤0.69).

Chapter Six

Post-impact Responses of Benthic Foraminifera to Metal Pollution in Restronguet Creek: Synthesis and Discussion

6.1 Introduction

This chapter investigates the relationship between the natural (salinity, temperature, carbon-nitrogen ratio (C/N), sediment grain size and mineralogy) and the anthropogenic data (water quality {acidity and metals} and sediment bound metals) with the foraminiferal data (standing crop densities, species distribution, absence of key species, metal bio-accumulation and the proportion of deformed tests). The time series data from Restronguet Creek (Enclosure 1a) have been used to identify post-impact changes that have occurred after the discharge of acid mine drainage from Wheal Jane tin mine in January 1992. The control estuary (Enclosure 1, b-d) data are used to delimit anthropogenic over natural influences.

6.2 Foraminiferal responses to anthropogenic and natural influences

i) Standing crop density

The majority of stations in Restronguet Creek (Enclosure 1a) show an increase in standing crop density between 1992 and 1996, most particularly with the colonisation of the longer term barren stations D1, C19, K20 and H23 (station BY28 was only barren in autumn 1992). Apart from sediment metal concentrations and river water quality the other factors (e.g., salinity, temperature, percentage organic carbon, the C/N ratio and sediment grain size) which may influence foraminiferal ecology, have not changed measurably with time and are unlikely, therefore, to account for this increase. There is no observed trend shown by any of the estuaries between high productivity (standing crop) and each variable, particularly the C/N ratio and percentage carbon (Hart and Thompson, 1974). The exceptions to this are the salinity and temperature in Restronguet Creek and the Fowey Estuary (Enclosure 1, a and c). Seasonal salinity in Restronguet Creek shows an association with seasonal standing crop density which is consistently positive, often being significant and occasionally strong (spring and summer). A similar trend is shown by the Fowey Estuary (Chapter Five, Table 5.8). It is evident, therefore, in Restronguet Creek and to a lesser extent in the Fowey Estuary, that standing crops increase with increasing salinity. This appears to be coincidental with the late spring and summer blooms (Ellison, 1984) in each case. The less than unity values shown suggest that an absolute direct relationship does not exist and this is supported by the frequently occurring weak linear trends shown in standing crop distribution down the Creek. No such routinely occurring significant relationship is shown by the other control estuaries, which have salinity profiles comparable to Restronguet Creek and similarly show weak linear trends in standing crop distribution down each estuary. Weak linear and seasonal trends are particularly pronounced in the Fowey Estuary which has relatively low density standing crops at the head of each subsidiary creek which corresonds with lower salinity (Chapter Five, Section 5.2.2,*iii*). The great statistical variation and weak relationships shown by the control estuaries (Chapter Five, Tables 5.6, 5.8 and 5.10), particularly by the Avon and Erme estuaries, suggests that foraminiferal densities in these estuaries, are not entirely predictable based on the measured parameters of salinity, temperature, percentage organic carbon, the C/N ratio and sediment grain size because of the patchy distribution behaviour of the foraminifera (Lynts, 1966; Lee and Müller, 1973; Buzas and Sen Gupta, 1982;

Murray, 1991). This behaviour may also account for the poor linear trends shown by the Restronguet Creek data and the spatial distributions shown in the mid- to low Creek. Lueck and Snyder (1997) conclude that variation in the nutrient content and chemistry of the pore water may attribute to the standing crop distributions shown in North Carolina (USA) but, with the exception of pH, these were not measured in Restronguet Creek or the control estuaries. It is generally apparent for all the estuaries that the lowest standing crop densities appear in the winter when they are considered to be dormant (Murray, 1968) and highest in the summer.

In Restronguet Creek, the rare occurrence of a significant negative association between standing crops and metals (1995) would appear to be coincidental with the increase in metal concentrations in 1995 and 1996 (Chapter Five, Table 5.5, d and e). The data show, however, that with the exception of station P10, the upper Creek stations D1, C19 and K20 (Enclosure 1a) have the lowest standing crops, but the highest sediment concentrations of Al, Cu, As and Zn. This is in conjunction with the lowest recorded salinity and proximity to the discharge point. With the exception of Station K20 (barren during all seasons 1992 - 1994) there is a seasonal trend shown by the upper stations D1, C19, and, mid-creek station H23 with respect to non-colonisation between autumn 1992 and spring 1994 (inclusive). Non-colonisation was more common in the winter and to a lesser extent in the spring and autumn (in that order) but none were barren in the summer. This coincides with high recharge rates and water flushing (Chapter One, Section 1.5.2) within the mines during these seasons, especially in the winter and poorer water quality (metals and acidity) between 1992 and 1994 (Chapter Four, Figures 4.17 and 4.18). The very much higher sediment metal concentrations at station P10 (Enclosure 1a) reflect an historical source originating from an old smelter at that location (Chapter Four, Section 4.7.3,*i*). The elevated metal concentrations at this station show no relatable influence on the standing crop densities (Chapter Five, Section 5.2.2,*i*).

The longer period of non-colonisation at station K20 probably reflects the severity of the impact caused by the major discharge in January 1992 on an area which, historically, suffered little exposure from mining practices within the River Kennell catchment (Chapter One, Figure 1.6). There had also been decades of relatively good mine water quality (Cambridge, 1995) and low discharge emanating from the Carnon Valley and particularly from the Wheal Jane and Mount Wellington mines (Chapter One, Section 1.5.2). Furthermore, prior to the discharge, the spit of land which physically separates the two rivers may have prevented small volumes of acidified mine water entering the Kennell from the Carnon Valley, although there is probably a subsurface connection between the two rivers (Chapter One, Figure 1.6). The aerial photographs taken at the time of the main discharge in January 1992, show the contaminated plume from the Carnon River being tidally introduced into the River Kennell, which met little resistance as the channel flow is quite gentle (Chapter One, Section 1.6,*i*). The introduction of mine waste material into the Kennell from the lower Creek (PI30) supports this assumption (Chapter Four, Section 4.4.2,*i*). It is possible, therefore, that the foraminifera colonising station K20 in the Kennell may be less tolerant of metal pollution, whereas, the assemblages on the Carnon side of Restronguet Creek, which have been subjected to centuries of acidified metal pollution, show a more rapid recovery. This may suggest the presence of within species adaptation (McNeilly and Bradshaw, 1968; Bryan, 1974; Bryan and Hummerstone, 1971; 1973b), as established for other organisms in Restronguet Creek (Chapter One, Section 1.3.3). For the foraminifera, however, this requires further investigation (Chapter

Seven, Section 7.2), although Sharifi (1991) suggests that there is some suggestion of adaptation shown by his research.

There is no observed connection shown between the distribution of standing crop densities and metal concentrations in the control estuaries, although, as with Restronguet Creek, the lowest densities appear in the upper estuary of each location and the subsidiary creeks of the Fowey Estuary in particular (Enclosure 1c). There would appear to be a seasonal association with the non-colonisation at stations HP2 - 4 in the Erme Estuary (Enclosure 1b), which unlike Restronguet Creek were all barren in the summer. There are no obvious reasons which may account for this and there are no observed relationships shown between standing crops here and the other variables, apart from lower salinity and a proximity to the main channel. It is possible, therefore, that the foraminifera at stations HP2 and HP3 may undergo greater physical disturbance due to varying channel flow and increased variation in the abiotic variables. It would appear that at station HP4, however, there may be some deleterious effect on the foraminifera originating from sewage discharge via. the open stream at Holbeton Point (Chapter One, Section 1.6,*ii*). In addition, easy vehicular access to Holbeton Point may facilitate illegal waste disposal, some of which may be toxic, e.g., farm slurry. This area of the Erme Estuary may require further investigation.

The Fowey Estuary (Enclosure 1c) is the only control estuary to show a negative relationship between all metals and standing crop density but only Cu and Zn are significant and may be available to the foraminifera. The Avon Estuary (Enclosure 1d), however, shows a positive relationship with respect to these metals which suggests that concentrations are at toxic levels in the former estuary but not in the latter, which may be at beneficial levels. As trace amounts both these metals are necessary to the health of most organisms (Otte *et al.*, 1991; Clark, 1992; Caffrey and Keating, 1997) but uptake (and bio-accumulation) is metal species specific (Bryan and Langston, 1992) and dependent upon pH levels (Gray, 1994). The extensive use of Cu and Zn oxide based boat anti-fouling paints in the Fowey Estuary, particularly in the lower estuary near the china clay port, may be the source. The highest concentrations of Cu and Zn (and also Al, Fe and Pb), on the west side, were present in the sediments from station G13 in the lower estuary (Enclosure 1c) in the boat pool (Chapter Four, Section 4.7.3,*iii*). This is in addition to that contributed by the abandoned Cu and Zn mines within the Bodmin granite (Chapter One, Section 1.5.1,*iii*). This is consistent with the results of Stubbles *et al.* (1996a) using a cold 10% HNO_3 method of extraction. The small number of boats moored on the Avon Estuary are unlikely to contribute excessive amounts of Cu and Zn to the estuarine sediments and certainly none would have been derived from past mining which was for silver-lead (Chapter One, Section 1.5,*iv*). The lack of an association shown by the Erme data (Chapter Five, Table 5.7) probably reflects the low boat population relative to the other estuaries and again only silver-lead was mined within the catchment. The average concentration of Cu in the control estuaries was highest in the Fowey Estuary with the Avon second (Appendices 1.2, 1.3 and 1.4). In the Erme Estuary, however, the Zn concentrations were the second highest. In all the estuaries there is a significant and sometimes strong relationship between Cu and Zn which may indicate a common source (Chapter Four, Tables 4.8 - 4.11). In Restronguet Creek and to a lesser extent in the Fowey Estuary the sources would be the abandoned mines and the weathering of metalliferous veins, in addition to more recent sources (e.g., boat anti-fouling paints). The use of anti-fouling paints in Restronguet Creek would not be high, particularly above stations P10 and TW27

(Enclosure 1a) because high rates of sediment accumulation have narrowed the draught and few boats can navigate the shallow channel to reach the moorings above these stations (Chapter One, Section 1.6,*i*). At the boat yards in the lower Creek anti-fouling paints are used and would contribute Cu and Zn to the sediments. In addition, other metals associated with boat repair and storage may also contribute metals to the sediments (through the decay of chains and galvanised fittings, e.g., rusting iron). This may contribute towards the poor linear trend shown by the sediment metal distribution, particularly on the north side of the Creek which shows either a small reduction in metal concentration or none at all between stations D1 and CY16 (Chapter Four, Section 4.7.3,*i*). In the Erme Estuary the significant but never strong relationship shown between Cu and Zn probably reflects the negligable inputs from boat anti-fouling paints, animal feeds and agricultural dressings, such as Cu, Zn and Pb based fungacides (Phinney and Bruland, 1997). In the Avon Estuary, however, the strong relationship between Cu and Zn may reflect regular use of anti-fouling paints, in greater amounts but not to toxic levels.

***ii*) Changes in species diversity, distribution and dominance in Restronguet Creek**

The number of species colonising Restronguet Creek has remained unchanged but the occurrence of lower values of H(S) which routinely occurred in Restronguet Creek between 1992 and 1994, compared with the control estuaries, has declined. The more even species distribution in Restronguet Creek after 1994 accounts for the increase in H(S), notably with the increased proportions of *Ammonia beccarii* and *Elphidium williamsoni*, in conjunction with a decline in the proportions of *Haynesina germanica* and instances of its assemblage dominance.

Of the species present, the distribution of *E. williamsoni* has been the most dynamic, being less predictable both temporally and spatially throughout the period of study. After 1995, *E. williamsoni* exclusively dominates all assemblages in Restronguet Creek in the winter and autumn and, in 1996, frequently dominated or co-dominated the assemblages in the mid - to low Creek in the summer with increased proportions in the spring. *Haynesina germanica*, however, remains the dominant species at the upper Creek stations D1, C19 and K20, and the mid - Creek station TC6, in the summer, and at all stations in the spring (Enclosure 1a).

As previously noted, there have been no changes in the naturally occurring variables from year to year to account for this, but changes have occurred in the anthropogenic variables; water quality (metals and acidity) and sediment-bound metals. During the years 1992 and 1994 a significant negative relationship is shown between *E. williamsoni* and metals (with the exception of Ni and Pb in 1992 and As in 1994) but during 1995 and 1996 the correlations were all insignificant and rarely negative. The distribution of assemblage dominance by *E. williamsoni* was erratic in autumn 1993 and the correlations for that year are not significant, although they are negative (except As). Between January 1993 and June 1994 the quality of the river water (metals and acidity) entering the Creek was poor and the profile was erratic (Chapter Four, Section 4.5,*i* and *ii*). This may be significant with respect to the distribution of *E. williamsoni* during that period, particularly as a time-lag response. The correlation between the metals Al, Fe, Cu, Ni and Zn and *H. germanica* in 1994 are positively significant and for Pb the relationship is strong. For the other years there are no significant relationships shown. The proportions of *A. beccarii* have increased over time but its relationship with the sediment-bound metals Al, Cu, Ni and Zn is only negatively significant in 1996. The frequently occurring weak relationship shown between sediment-bound metals and species distribution may also be due to the poor linear trend shown by sediment metal data, which reflects localised inputs, for example, at station P10 in Restronguet Creek (Enclosure 1a). Mixing by bioturbation (Del Valls *et al.*, 1997), errors in dilution during the extraction and analytical process may also be the reasons.

In summary, it is evident by the calcareous species distribution in the control estuaries (Chapter Five, Section 5.4.2, *ii* - *iv*) and the changes in species proportions and distribution that have occurred in Restronguet Creek between 1992 and 1996, that *H. germanica* is an r-strategist. As a pioneering species, *H. germanica* has successfully colonised less favourable environments and continues to seasonally dominate the assemblages within the upper Creek that are in closest proximity to the discharge source. With the improvement in water quality *E. williamsoni* and *A. beccarii* have increased their porportions and occurrence of assemblage dominance and, hence are K-strategists (Ellison and Peck, 1983), species competitors, particularly *E. williamsoni*. This species is successfully competing with *H. germanica* to become the most important, widespread species in Restronguet Creek. Overall, it appears that *E. williamsoni* and *A. beccarii* are more sensitive to metal toxicity than is shown by *H. germanica*, which may be more specialised (Stubbles *et al.*, 1996a). It is apparent, therefore, that species competition in Restronguet Creek may be a more important regulator after 1994 with improved water quality in terms of metals and acidity.

***iii*) Comparisons in species distribution and the absence of the agglutinating foraminifera in Restronguet Creek**

It is apparent that the control estuaries have distinctively different species compositions relative to that of Restronguet Creek (Chapter Five, Figures 5.17 -

5.19). Much of the dissimilarity shown between the control estuaries and Restronguet Creek is due to high proportions of *Miliammina fusca* in the upper part and creeks of each control estuary. *Miliammina fusca* only penetrates into the mid - estuary areas, as a dominant species, during the dormancy periods of the calcareous species; e.g., in the Erme Estuary (Stubbles, 1995) during the winter (Chapter Five, Section 5.4.2,*ii*). Conversely, spatial similarity only exists between Restronguet Creek and each control estuary when the proportions of the agglutinating species are reduced relative to the calcareous component; e.g., the Fowey Estuary in the summer. The mid - to low estuary area of the Fowey shows a similar seasonal trend to that shown by Restronguet Creek, with *H. germanica* being the most important species in the spring and summer and *E. williamsoni* dominant in the winter and autumn. In the Erme and Avon estuaries, there were increased proportions of *H. germanica* in the summer, particularly in the lower estuary. It is apparent by the significant association shown between *H. germanica* and salinity, and, more occasionally with temperature (Chapter Five, Tables 5.6 and 5.10) that this species favours higher salinity and temperature regimes. Reduced competition from other species and a response to increased nutrient supply, may also be the reasons for its increased proportions in the summer (Buzas and Sen Gupta, 1982).

Miliammina fusca does not appear to be as well established in the Fowey Estuary relative to the Erme and Avon, but as with the latter two estuaries, this species is largely limited to the upper estuary where salinity is lowest. Relative to the other estuaries, higher salinities were recorded in the Fowey Estuary which is probably due to dredging in the lower estuary (Chapter One, Section 1.6, *iii*). This may be influencing the distribution of *M. fusca* which shows a significant negative correlation with salinity, particularly in the Fowey Estuary (Chapter Five, Tables

5.6, 5.8 and 5.10). It could also be the case that the contamination from the abandoned mines may be more concentrated in the summer due to lower river flow. The additional depth generated throughout the estuary by the dredging probably does not limit the distribution of *M. fusca* as this species has been found living (stained) to depths of 35m within lower salinity bottom waters (Hermelin, 1987). The short core taken from the Fowey Estuary shows an all calcareous fauna below 34cm with an approximate date of 1885 (Pirrie *et al.*, 1999). It is evident from present day and historical data, therefore, that Restronguet Creek and the Fowey Estuary have had similar species colonisation histories and the more recent colonisation by the agglutinating species, into the latter estuary, has taken place after the main pulse of mining contamination had ceased and probably before dredging commenced in 1904.

The continued absence (as living and dead) of the typical estuarine/saltmarsh agglutinating foraminifera (Adams and Haynes, 1965) in Restronguet Creek and short core data indicates that the most recent discharge (January, 1992) and other factors (e.g., mineralogy, Chapter Five, Section 5.7) are not accountable for the observed absence. Much earlier, historical impacts may have been responsible for their initial removal but only deep core data to pre-mining levels will establish if this the case. Due to the tolerance thresholds of *M. fusca*, only passive introduction into Restronguet Creek, for example, through the guts of fish, on the wings and feet of birds (Almogi - Labin *et al.*, 1992) will enable agglutinating foraminiferal colonisation, if the environmental conditions favour it. The dominance of the calcareous species in Restronguet Creek, within areas offering similar salinity and temperature regimes to those found in the control estuaries, particularly in the upper Creek (Chapter Five, Section 5.7.2), is something of an anomaly given the deleterious acidic conditions which has corroded the calcareous tests and depleted the dead assemblage (Stubbles *et al.*, 1996b). The continued assemblage dominance by *H. germanica* (spring and summer) at stations D1, TC6, C19 and K20 in Restronguet Creek appears to be in contradiction to the environmental preferences shown by this species (higher salinity and temperature regimes). These upper estuary and creek areas are commonly dominated by *M. fusca* all year (Hayward *et al.*, 1996). It would appear, therefore, that the calcareous species are unusually tolerant of the low pH conditions (pH range of 3.2 - 6.9) in Restronguet Creek (Stubbles *et al.*, 1996b). Other research has shown that calcareous species prefer not to colonise acidified environments (Parker and Athearn, 1959; Bandy, 1960; Scott *et al.*, 1991; DeRijk, 1995; 1996; DeRijk and Troelstra, 1996) but which are typically colonised by *M. fusca* and other agglutinated species as in the Erme, Fowey, Avon, Looe and Axe estuaries (Chapter Five, Section 5.7.2). It may be for the following reasons, individually or combined, that the agglutinating species are absent in the acidified upper estuarine area of Restronguet Creek:

- the agglutinating species which use carbonate cement cannot maintain their test structure and growth under acidified conditions (Murray, 1973);
- the feeding strategy of the agglutinating species, which is considered to be detrital rather than carnivorous, may be inhibited;
- the calcareous taxa have become specialised and out compete other species;
- more directly, metal enriched pore and river water, with enhanced metal solubility under acidic conditions may be detrimental to the agglutinating foraminifera; and
- the absence of a mechanism by which metal toxicity may be ameliorated.

It is apparent from the work of Bender (1995) that the agglutinating species *M. fusca*, *Jadammina macrescens* and *Trochammina inflata* use organic and not calcareous cement to bind the grains together, although the grains used by *M. fusca* are more looslely bound relative to the other two species. *Jadammina macrescens* and *T. inflata* also have the additional benefit of an outer as well as an inner organic layer (Bender, 1995) which may provide greater protection against acid dissolution. *Jadammina macrescens* and *T. inflata* use predominately clay and muscovite mica to build their tests (Scott *et al.*, 1998) and generally do not include carbonate material (e.g., shell fragments) which would be prone to dissolution. More variable mineral types, including carbonate material are used, however, by *M. fusca* for test construction (Chapter Five, Section 5.7.2) and under acidified conditions this may be a potential weakness. It may also be significant that the specimens taken from the slightly acidifed environment of the Fowey Estuary contain little carbonate material, preferring to use minerals instead (Chapter Five, Section 5.7.2). The concentration of heavy minerals and daily removal of marine derived sediments (containing high amounts of shell debris, Chapter Four, Section 4.4.4) may also explain the mineralogy of the tests taken from the Fowey Estuary. The greater use made of shell fragments by specimens of *M. fusca* taken from the Erme and Avon estuaries, which are not acidified and dredged, supports both suggestions. The absence of agglutinating foraminifera (living and dead) at St Clements, which is not acidified, would preclude acid stress as the cause of the continued widespread absence. Furthermore, the durability of the agglutinated tests has been determined by the postmortem dissolution experiments of Alve and Murray (1994;1995b) and attests to their ability to persist within acidified environments. This is supported by the findings of Setty and Nigham (1984) who found agglutinated species preferentially colonising areas polluted by high organic loadings and acid discharge.

Although DeRijk and Troelstra (1997) have reported that agglutinating foraminifera may make use of diatoms in their diet, their preferred food source is detrital organic carbon. It has implications for these species that Cu and other metals are known to form organic complexes and preferentially bind to organic carbon (Chester, 1990; Bryan and Langston, 1992). If consumed by the agglutinating species metal enriched detritus, particularly by Cu, may induce a deleterious effect (Sharifi, 1991; Sharifi *et al.*, 1991).

It is evident by the distribution of *M. fusca* in the control estuaries that it is seasonally out-competed by the rotalid species. The temporal and spatial distribution and dominance shown by *E. williamsoni* in the Erme and Avon estuaries and with *H. germanica* in the Fowey Estuary, suggests that these species may prevent *M. fusca* colonising new locations. This response to competition is more pronounced in the Fowey Estuary, whereby the spatial distribution of *M. fusca* shows greater limitation. This may reflect past mining influence, in addition to the previously discussed higher salinity and temperature regimes in the main channel, particularly at and below station CH5 (Enclosure 1c), the conditions of which may favour the calcareous species (Buzas, 1969). It may be significant that the extent and period of metal mining affecting Restronguet Creek and the Fowey Estuary are similar, whereas the Erme and Avon estuaries, which physiologically closely resemble each other, were least influenced by mining (Chapter One, Section 1.5.1). The out-competed behaviour shown by *M. fusca* in its spatial and temporal distribution in the control estuaries, would suggest that this species may be an opportunist, and only expands its spatial distribution when the environmental conditions favour it and most usually when the calcareous taxa are dormant or absent (Setty, 1984).

Bresler and Yanko (1995) suggest that the calcareous species may have mechanisms that enable them to remove excess Cu. This function may only be available to the calcareous species that secrete a test and those agglutinating species that secrete calcareous cement. The three agglutinating species, *M. fusca*, *T. inflata* and *J. macrescens* do not posess this facility. This remains, however, speculative as the elimination of metals by the foraminifera is poorly known and consequently, all such interpretations are constrained.

_iv_) Changes in the proportions of deformed tests

Through time, there has been a substantial decrease in the proportion of deformed tests in Restronguet Creek and the frequency of occurrence has also declined, with numerous stations recording zero in winter 1996. In autumn 1996 the majority of values are below 5% which is comparable with the values observed for the control estuaries. No juvenilles showing test deformity have been observed after 1995. This may be indicative of reduced metal availability (e.g., in solution) and thereby, a longer exposure time required for a deleterious effect (e.g., test deformity) to be manifested. None of the variables measured can account for this decline but that the decrease has coincided with improved water quality (both metals and acidity), most particularly from summer 1995, which saw a sharp reduction in the amount of water stored in the mine workings due to low recharge.

The high values of deformed tests observed in the Erme and Avon estuaries were random and infrequent and the majority of values were below 5%. There were also no significant correlations shown between the proportion of deformed tests and sediment metal concentrations in the control estuaries. The proportion of deformed tests was least in the Fowey Estuary, which never exceeded 5%. The likely reason for this is the dredging of the harbour which has a dual effect by the removal of historically contaminated sediments within the estuary and by creating a deeper water channel which would enhance dilution and dispersal of freshly derived contaminants originating from the abandoned mines. The daily removal of predominantely marine derived sediments (which would account for the low proportions of transported - in tests) may also explain the presence of high amounts of heavy minerals observed in the sediments which originated from the Bodmin Granite (Chapter Four, Section 4.4.4) and have become concentrated within the Fowey sediments (Pirrie and Camm, 1999). The occasional and marginally low pH pore water values recorded in the Fowey Estuary were well above those observed in Restronguet Creek. Apart from a low occurrence of test opacity in the Fowey Estuary, the low pH conditions do not appear to have had an adverse effect upon the foraminifera by the mobilisation of sediment-bound metals, even though the former location has the second highest Cu concentrations which is known to be toxic to the foraminifera (Sharifi, 1991; Sharifi *et al.*, 1991). It would appear, therefore, that sediment metal solubility may be too low to affect the foraminifera and the lower proportions of deformed tests supports this.

The micro-analysis of the deformed and undeformed tests has established a quantified difference between deformed and undeformed tests using laser ablation with higher metal concentrations being recorded in the former (Chapter Five, Section 5.9). Although this new approach to the micro-analysis of calcareous tests was a limited study, a strong positive correlation has been determined between deformed tests and elevated levels of sediment-bound metals (Chapter Five, Section 5.9). The earlier microprobe work carried out by Stubbles *et al.* (1996a) also found higher levels of Al, Fe, Cu and Zn in deformed tests relative to undeformed but the detection limits are much higher compared with laser ablation (1ppm with a spatial resolution of 20μm). Both the laser ablation data and the deformed data for the Restronguet Creek, stations D1, TC6, C19 and K20, correlate significantly with the sediment metal data (1996 only). By using the cold extractable 1M HCl method to leach metals from the sediments, Bryan and Langston (1992) conclude that the strongest correlations result between the sediment-bound metals and those within the organisms (Dr. Langston, pers. comm., 1996). This may explain the strong positive relationhip shown between the laser data and the sediment metal data. The negative relationship shown between the undeformed individuals and metals, which for Al and Cu is strong, suggests that these specimens may not bioaccumulate metals.

As previously observed (Chapter Five, Section 5.8.4), the weak and occasionally negative correlation shown between the proportions of deformed tests and sediment-bound metals, particularly in Restronguet Creek (between 1992 and 1996), is probably a statistical rather than an environmental anomaly, partly brought about by using percentages (closed data) which would induce the negative association (Swan and Sandilands, 1995). In addition, the inclusion of data from stations with low standing crops at which deformed tests were generally not observed after 1994, would also produce negative correlations and would not be ecologically representative (Chapter Five, Section 5.8.3). The omission of the pre-1994 zero data from stations D1, C19 and K20 (Enclosure 1a) which had the highest sediment metal concentrations (with the exception of station P10) and were closest to the discharge point, increases the instances of weak correlation. This is supported by the statistical analysis of the 1995 and 1996 data from these stations only (Chapter Five, Section 5.8.4,*i*). These data show there to be a significant and positive relationship between the proportion of deformed tests and the sediment-bound metals, particularly Cu and Zn. This corresponds with the data obtained for Cu by laser ablation (Chapter Five, Section 5.9).

The observed decline in the percentages of deformed tests down Creek (Enclosure 1a) does not correspond with the distribution of the sediment-bound metals, which do not show a strong linear trend. This is particularly evident with respect to station P10 which has the highest metal conentrations in the Creek but not the highest proportions of deformed tests. It is evident, therefore, that observed temporal and spatial changes in the occurrence of deformed tests rather than statistical inference are a more reliable indication of these post-impact changes throughout Restronguet Creek.

The occurrence of deformed tests noted by other workers has been attributed to a number of causes (e.g., hypersalinity, Almogi-Labin *et al.*, 1992). Arnal (1955) suggests that several influences in combination may cause the high occurrence of abnormal tests observed at various sample locations in the USA. Sharifi (1991), Sharifi *et al.* (1991), Alve (1991) and Yanko *et al.* (1998) have, however, attributed metal pollution to be the most likely cause of test deformity. More recently, Stouff *et al.* (1999) have identified causes other than pollution that may account for high proportions of deformed tests (e.g., hypersalnity, mechanical damage and acid dissolution). With respect to this research the natural variables (e.g., salinity and temperature) were observed to be at normal estuarine levels in the overlying water which did not vary beyond the wide ranging tolerance limits of the indigenous euryhaline species. The elevated levels of salinity within the pore water (44‰), particularly within the lower parts of each control estuary and Restronguet Creek, does not appear to adversely affect the foraminifera as some of the lowest proportions of test deformity are found here. Tests showing signs of mechanical damage were not regarded as deformed. It may be the case, however, that the acid polluted environment of Restronguet Creek may be a contributory factor in test deformity but the inter-related relationship between metals and acidity is difficult to separate (Stubbles, 1995; Stubbles *et al*, 1996a).

6.3 Sediment - bound metals and water quality

The ecological changes that have taken place in Restronguet Creek between 1992 and 1996 have done so despite there having been an increase in sediment metal concentrations. High levels of metals in the sediments, however, do not always equate with what may be available to an organism or bio-accumulated (Thomson *et al.*, 1984). Furthermore, concentrations within the sediments will usually be greater relative to the overlying water (Leppanen *et al.*, 1998) and this is the case in Restronguet Creek (Bryan and Langston, 1992).

The accumulation of metals in the sediments from Restronguet Creek are a mixture of point and diffuse sources (Chapter Four, Section 4.7.3,*i*). The point source is associated with the old smelter site within the mid-Creek area (Station P10) and shows the highest metal levels relative to other stations (Enclosure 1a). The atmospherically borne contamination from this site may also have contributed additional metals to the sediments on both sides of the Creek below station P10 (Enclosure 1a). Acid mine drainage originating from the Carnon Valley, leaching of sediment-bound metals under low pH conditions (Shine *et al.*, 1998) and overall changes in pore water chemistry (Salminen and Haimi, 1999) combine to provide the diffuse source, the effects of which are more difficult to trace and predict (Alve, 1995).

How much the pore water metal chemistry differs to that of the overlying water is not known, but pH was determined with varying success (Chapter Two, Section 2.1.1). The sediment removed for geochemical analysis was always oxidised. This suggests that chemical exchange and diffusion between the overlying water column and interstitial water may have taken place, and hence, the chemistry of the two waters may be closely similar (particularly at the sediment-water interface). Furthermore, fluxing between the two types of water produces changes in their chemistry and each can influence the other (Chester, 1990; Bryan and Langston, 1992; Lueck and Snyder, 1997). The observed tidal water film that persisted during each low tide in Restronguet Creek would indicate prolonged contact and mixing may occur between the two water types. Furthermore, as no living foraminifera were observed below the top centimetre of each core taken from Restronguet Creek and the control estuaries it is evident that the indigenous estuarine species are shallow infaunal (Buzas *et al.*, 1993; Goldstein *et al.*, 1995; Ozarko *et al.*, 1997) and, therefore, are likely to be influenced by both the overlying and interstitial water. It is evident also that the foraminifera remain within the oxidised zone, not having been found deeper (Boltovoskoy, 1966) and show no vertical migratory behaviour away from adverse conditions (Bernard, 1986; Alve and Bernard, 1995). The depth to which foraminifera penetrate the substrate does not appear to be controlled by grain size or species preference as found by Boltovoskoy and Lena (1969). The sediment grain size distribution and cohesiveness of the substrate may have an influence on how effectively the tidal water is vertically diffused, evaporated and drained, in addition to adsorptive processes (Bubb and Lester, 1994).

The difference in metal concentrations and pH of the surface water recorded at Devoran monitoring station at the head of Restronguet Creek and the fixed station at the mouth indicates the presence of a concentration gradient between the two (Chapter Four, Section 4.5). The gradational increase in pH down Creek in the overlying water column and pore water was similar, and each may be influenced by proximity to the discharge source and dilution by the incomming tide. Of the two waters, however, the pH of the pore water was always slightly lower. The presence of an acid gradient is supported by the frequent occurrence of full calcareous test opacity, particularly in the winter at the upper and mid - Creek stations, D1, TC6, TC8, TC9, P10, C19 and H23 with partial test opacity elswhere prior to summer 1994 (Chapter Five, Section 5.10).

It is known that metals alone cause negative responses by the foraminifera (Ellison *et al.*, 1986; Alve, 1991,1995; Sharifi *et al.*, 1991) but to what extent acidity alone affects foraminiferal ecology is largely unknown. It has been established, however, for other organisms, particularly fish (Beamish and Harvey, 1972; Bradford *et al.*, 1998), that reproduction is inhibited by increased acidity. The early work of Bradshaw (1961) found *A. beccarii* to be tolerant of low pH conditions and recalcified even after complete dissolution of the test had occurred. Sluggish feeding and reproduction followed complete dissolution and recalcification of the test and this may reflect heavy consumption upon the foraminiferal energy budget. Calcareous species avoidance of low pH environments has been detected by Phlegler and Bradshaw (1966) and Schafer (1970). DeRijk (1995) and Scott *et al.* (1991) suggested that this is why the agglutinated species occupy niches vacated by the calcaeous species. The precise causes of this avoidance strategy, however, were not determined.

The difference in foraminiferal ecology and the stronger statistical relationship shown between the proportion of deformed tests and metals shown by stations D1, C19, K20 and H23, supports the conclusion that the upper Creek has been both directly (primary metal enriched mine water discharge) and indirectly (secondary acid leaching) influenced by acid mine discharge into the river (Stubbles, *et al.*, 1996a). The mid - to lower Creek stations appear to be least affected by primary discharges and may reflect a greater influence from the secondary process of acid leached metals stored in the sediments. The variable pH experiments of Stubbles *et al.* (1996a) show that at pH 3.5 the highest metal concentrations were mobilised from the sediments.

In addition to a proximity to the discharge point, the upper stations may also be affected by changes in metal chemistry brought about by salinity. At lower salinities metals in solution are in a more toxic form (Bryan, 1985a; McLusky, 1989; McLusky *et al.*, 1986; Broman *et al.*, 1991). The significant (which in some cases is strong) statistical association shown between salinity and standing crops in Restronguet Creek suggests that the salinity profile is indirectly reflecting metal and acid dilution and dispersal with a potential reduction in metal toxicity down the Creek with increasing salinity (Chapter Four, Section 4.5,*i*). As there is both temporal and spatial variation in salinity it is likely that those areas having the lowest values due to position and season (winter) will suffer greater metal toxicity. At increased salinities approaching normal marine, particulate uptake of metals is enhanced, thus removing metals from solution by settling and hence, reducing their availability (Mayer, 1982a, b; Chester, 1990; Hardman *et al.*, 1993).

The remedial action taken (Chapter One, Section 1.5.2) and the resultant improvement in water quality emanating from Wheal Jane tin mine may explain why colonisation of previously barren stations has occurred despite the increase in sediment-bound metals between 1992 and 1996. This increase in metal accumulation within the sediments suggests removal of dissolved metals to the particulate phase with increasing pH (Krumbein and Garrels, 1952; Trefry and Metz, 1984; Wren and Stephenson, 1991; Yahya, 1994; Stubbles *et al.*, 1996a; Shine *et al.*, 1998). Somerfield *et al.* (1994a) detected no increase in sediment metal concentrations immediately after the discharge in January 1992 and conclude that the pH of the overlying water column was too low to allow precipitation. Somerfield *et al.* (1994a,b) also conclude that the interaction of a large number of variables (e.g., Fe-oxide binding) would influence the chemistry of the interstitial water. Iron coated sediment grains were observed in the sediments taken from Restronguet Creek and to a lesser extent from the Fowey Estuary (Chapter Four, Section 4.4.4). The strong statistical relationship shown between sediment-bound Fe and other metals from Restronguet Creek and the Fowey Estuary also suggests metal scavenging. This scavenging behaviour which enhances metal stability is, however, dependent upon the pH of the pore water and overlying water column (Benjamin and Leckie, 1981; Johnson, 1986; Boon *et al.*, 1998; Milam and Farris, 1998) and toxicity is metal specific within a range of pH values (Shiller and Boyle, 1985; Freda, 1991; Ankly and Schubauer-Berigan, 1995). For this reason the highest proportions of colloidal iron were present in the Fowey River and least in the acidified Carnon River (Mill, 1980). The addition of low pH appears to be a major controlling factor in Restronguet Creek with respect to metal solubility (Bryan, 1985b).

In summary, therefore, the acid mine contamination originating from Wheal Jane tin mine and the other abandoned mines within the Carnon Valley has exposed the foraminifera to the combined pollution sources of acid dissolution, metals in solution (in an available form) and contributed additional metals to the sediments in Restronguet Creek. The naturally occurring variables (e.g., salinity and temperature) may also have some influence on acid and metal toxicity.

Chapter Seven

Conclusions

7.1 Post-impact changes - conclusions

It is the overall conclusion of this research that no one response shown by the foraminifera should be taken as solely indicative of a deleterious impact. In combination with the control data, the sum total of the changes shown by foraminiferal assemblages in Restronguet Creek can be viewed as anthropogenically driven and most probably not caused by naturally occurring variation. The post-impact changes in foraminiferal ecology that occurred in Restronguet Creek between 1992 and 1996 and conclusions are, therefore:

- the colonisation of the long term barren stations; D1, C19, K20 and H23 and the overall increase in standing crop densities suggests a response to severe metal pollution followed by mine water remediation. Standing crop densities remain, however, less predictable due to the patchy distribution behaviour of the foraminifera and also because of the instability of the local mine water quality;
- it is apparent that the absence of data (barren samples) causes problems in statistical inference that may be environmentally unrepresentative. While barren samples are significant in their own right, no other biological information can be gained from such samples;
- in the absence of any major changes in the naturally occurring variables the spatial and temporal changes in species distribution would appear to be a response to reduced metal pollution. The generalist, *Elphidium williamsoni* has gained in importance, while the specialist, *Haynesina germanica* has declined;

- the low abundance and limited distribution shown by *Ammonia beccarii* prior to 1995 suggests that this species is least tolerant of metal pollution. Its increased abundance and more widespread distribution after 1995 has led to a more even species distribution;
- these changes in species distribution suggests the following order of species tolerance: *H. germanica*>*E. williamsoni*>*A. beccarii*;
- competition may be an important regulator of the calcareous species distribution after 1994 but, prior to this, metal pollution was severe enough to exert a modifying influence;
- the diversity of the live (stained) assemblage remains low due to the continued absence of the agglutinating species;
- the absence of the agglutinating species in Restronguet Creek and within the environs of the Carrick Roads may not have been caused by the major discharge in January 1992. At present species competition may be the controlling factor;
- the geographical distribution of the agglutinating species in south-west England would suggest that the frequency of occurrence and abundance of these species increases from west to east. This follows a similar trend exhibited by the geology and mining of polymineralic ores, particularly Cu;
- the proportions of test deformity have declined spatially and temporally over time. The levels in Restronguet Creek are approaching those observed in the control estuaries and a background level of between 3% and 5% would be regarded as usual for an area draining metalliferous geology and previous metal mining;
- analysis carried out during this study has established that there is a link

between deformed foraminifera and metal accumulation in the tests with high concentrations of metals in the sediments;

- full and partial test opacity, with the former being particularly severe within the upper and mid - Creek, are no longer evident. This suggests that there has been a decrease in the amount of acidified water entering the Creek; and
- the proportions of transported-in species have increased with increasing pH, which again supports changes in water pH.

With the exception of the sediment-bound metals, there have been no year-by-year changes in the other variables that may account for the changes shown by the foraminifera. It would seem, therefore, that these changes have coincided with the long term benefits of the remediation programme inaugurated by the Environment Agency in January 1992, which has delivered, particularly after 1994, improved water quality entering the Carnon River from Wheal Jane tin mine in terms of metals and acidity. It has been shown, therefore, that even set against a background of long term contamination, an impact can be detected through the responses of the foraminifera, while other organisms appear not to have so responded. The main discharge involved a combination of factors and complex interactions which produced both primary (metals and acidity) and secondary (acid metal leaching) impacts on the estuarine environment and thereby negative responses by the foraminifera.

The foraminiferal results from the control estuaries, particularly the Fowey Estuary, show that with time, the estuarine environment is capable of recovery. This study has shown that, at the present time, a potential risk remains as the water levels in the mines (and highly variable recharge) form the main control on water quality and discharge. In addition, the discharges emanating from the other mines in the Carnon Valley, particularly via. the County Adit, are also sources of acid mine water pollution. It is anticipated that eventually the mine faces will leach back sufficiently as not to pose an environmental risk.

7.2 Future research

This research has shown that foraminifera appear to respond to water quality in terms of metals and acidity, rather than metals bound to sediment grains. It would be advantageous, therefore, that in future field and laboratory studies techniques be developed that enable micro-analysis of the pore water chemistry (metals and pH) at intervals that would be relatable to the size of the foraminifera.

The Laser Ablation Inductively Coupled Plasma results have shown that micro-analysis can give useful information on metal accumulation and should continue to be developed in the future. Only through such analysis can the causes of test deformity be determined. The micro-analysis of individual tests, chambers and parts of chambers may define how the foraminifera ameliorate the effects of metal pollution, the ways in which metals enter the organism and if within species adaptation exists. This approach is not applicable for use on agglutinated tests because of their heterogeneous nature.

Deep coring may locate the levels at which these species appear and disappear and with the chemistry of the sediments, the reasons for their absence may be determined. Mesocosm and culturing experiments using *M. fusca* may further explain the tolerances of the agglutinating species and how metal pollution influences their distribution. This work does not appear to have been undertaken, probably because the complexity of their particular natural environment which, means it would require sophisticated technology to achieve it in the laboratory.

Appendices

Abreviations for appendices: SC/T - total standing crops, %T - percentageof total, %sp - percentage of species, DSC/T - total deformed standing crops, %Cal - percentage of calcareous species that are deformed.

Wherever possible percentage values have been rounded up or down.

Appendix 1.1a

Atomic Absorption Spectroscopy

Sample	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1/92	1077	6408	618	53	8	175	1350	ND	2375
D1/92 R	1180	6650	705	60	8.5	175	1505	ND	2500
C19/92	1325	9000	643	63	7	230	1725	ND	1375
C19/92 R	1400	9665	700	65	7.5	255	1850	ND	1455
D1/93	1058	5250	500	45	6.5	125	1225	1	1325
D1/93 R	966	5080	485	45	6.75	115	1150	1	1500
C19/93	1095	6250	525	55	7.5	230	1125	ND	775
C19/93 R	960	5835	465	50	7.5	245	985	ND	850
D1/94	1350	10482	693	75	10.5	340	1450	1.5	1813
D1/94 R	1500	11300	800	85	12	385	1675	1.5	2050
C19/94	1055	6500	475	50	6.25	70	975	ND	1025
C19/94 R	1065	6665	485	50	6	70	1000	ND	1000
D1/95	1125	6830	615	80	5.75	215	1275	ND	3075
D1/95 R	1175	7000	665	80	6.25	240	1400	ND	3450
C19/95	1430	9625	775	100	12	268	1563	1	3100
C19/95 R	1515	10250	835	110	13	250	1575	1	3100
D1/96	1350	10375	683	100	14.25	250	1360	ND	3930
D1/96 R	1225	9000	600	90	15	245	1200	ND	3500
C19/96	1505	11125	910	110	16.75	355	1825	ND	4875
C19/96 R	1475	10250	935	115	17	355	1875	ND	5125
S20/93	560	4000	8	32	5.75	ND	55	ND	20575
S20/93 R	585	4120	7.5	30	5	ND	57	ND	23050
G13/94	510	2075	40	27.5	4.75	ND	85	ND	3175
G13/94 R	575	2360	45	30	4.25	ND	95	ND	3550
A12/95	600	3058	14.5	15	7.5	ND	47	ND	15925
A12/95 R	575	3015	13.5	14.5	7	ND	47.5	ND	15650

Replicated data. Values in ppm (parts per million). R - denotes replicate.

	Al	Fe	Cu	Pb	Ni	Zn	As
Blank	2	2	0.5	0.5	0.5	1	1
Detected	0	0	0	0	0	0	0
Certified values	8.5%	4.4%	39.3	21.9	49.3	172	20.7
Extracted	4%	-	16	6.5	19	78	7.5

Blank data (Aristar, values in ppb) and detection values for each blank. The values for the certified reference material (MESS 2) and the concentrations extracted are in ppm except for the oxides for Al and Fe which are as percentages. Atomic Absorption Spectroscopy was not able to detect metal concentrations in the blanks. The detection limits for Cd and Cr using AAS are 2ppm and 4ppm respectively.

Laser Ablation Inductively Coupled Plasma

	Al	Fe	Cu^{63}	Cu^{65}	Zn^{64}	Zn^{66}	Pb	Ni	Ca
Resin 1	8.896	-12.73	-0.117	-0.144	-0.011	-0.024	-0.063	-0.027	-13.067
Resin 2	9.896	-12.65	-0.101	-0.105	0.045	0.023	-0.05	-0.286	-6.813
D.L	0.326	16.972	0.24	0.275	0.274	0.293	0.09	0.643	63.312
St. 1	99.99	100	99.99	99.99	100	99.99	100	99.99	100
St. 2	86.58	85.68	86.49	86.45	85.33	85.61	82.47	86.22	88.19
St. 3	72.77	85.68	75.98	75.35	74.8	75.23	70.82	75.19	74.6

Laser ablation values, as arbitary counts (raw data), for the resin stubs, detection limits (D.L.) and standards 1, 2 and 3.

Blank	Al	Fe	Cu^{63}	Cu^{65}	Zn^{64}	Zn^{66}	Pb	Ni	Ca
1	0	0	0	0	0	0	0	0	0
2	-0.035	-1.185	-0.033	-0.033	-0.005	-0.045	0.018	0.027	-3.853
3	-0.116	-15.90	-0.078	-0.094	-0.119	-0.103	-0.035	-0.284	-32.25
4	0.157	-5.61	0.195	0.191	0.18	0.158	-0.021	0.245	-6.15
5	-0.169	-10.08	-0.112	-0.117	-0.118	-0.143	-0.065	-0.145	-13.65
6	-0.155	-11.45	-0.112	-0.122	-0.114	-0.133	-0.063	-0.175	-15.56
7	-0.119	-12.413	-0.055	-0.076	-0.046	-0.08	-0.06	-0.115	-19.229
8	-0.185	-18.312	-0.098	-0.13	-0.128	-0.151	-0.7	-0.403	-21.848
9	-0.083	-9.682	-0.028	-0.52	-0.029	-0.04	-0.062	-0.303	-11.122
10	-0.163	-5.713	-0.108	-0.123	-0.125	-0.167	-0.067	-0.385	-12.868
11	-0.359	-71.819	-0.169	-0.256	-0.254	-0.302	-0.08	-0.554	-75.59
12	-0.168	-18.646	-0.046	-0.075	-0.052	-0.071	-0.063	-0.418	-56.725
13	-0.096	-14.096	-0.003	-0.023	-0.028	-0.002	-0.065	-0.467	-44.212
14	-0.173	-14.353	-0.088	-0.112	-0.112	-0.121	-0.065	-0.467	-44.212
15	-0.15	-9.629	-0.052	-0.065	-0.058	-0.066	-0.062	-0.339	-34.04
16	-0.188	-14.333	-0.079	-0.1	-0.095	-0.107	-0.064	-0.421	-40.105

Raw blank data for the laser ablation analysis (values as arbitary counts).

Note:
The blanks were run regularly throughout the days analysis and were subtracted from the samples to correct for minor changes (e.g. analytical drift). Using the three standard deviations of the blanks the detection limits were determined but these detection limits do not apply to the samples which changed due to the amount of material ablated. This has the effect of halving the detection limit if, for example, twice as much material is ablated. The detection limit is, therefore, applied to the raw data before standardisation. The change in the standard value, which are almost 100 in standard 1, is a reflection of changes in instrument sensativity through the days analysis. This drift was assumed to be linear and, therefore, a proportional correction was made.

Appendix 1.1b: Restronguet Creek, sediment geochemical data

station	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1A92	1077	6408	618	53	8	175	1350	ND	2375
TC6	1200	5500	767	80	12.5	ND	1825	1	3000
TC8	650	3335	215	40	4	175	750	ND	2050
TC9	725	3650	365	45	7.5	175	925	ND	2000
P10	1150	7335	700	95	10	250	1550	1	3550
PC13	855	6000	465	110	7	175	1075	ND	2100
CY16	1000	7335	535	70	4	215	1275	1.5	1900
C19	1325	9000	643	63	7	230	1725	ND	1375
K20	1550	9665	1050	85	9	320	1850	1	850
H23	680	4000	465	60	4.5	105	800	ND	1500
TW27	1045	6650	650	75	8	285	1450	1	3800
BY28	990	8500	615	80	8.5	320	1600	1.5	4500
PI30	1090	9665	650	90	6.5	250	1300	1	9500
station	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1A93	1058	5250	500	45	6.75	125	1225	1	1325
TC6	1110	5000	835	70	7	ND	1575	0.5	1400
TC8	625	3000	435	30	3.5	ND	525	ND	1050
TC9	800	3835	485	60	6	175	1000	ND	1100
P10	1690	15000	1100	190	17.5	430	2325	1.5	4375
PC13	670	4665	300	55	6	215	600	ND	750
CY16	1200	8335	715	80	8.5	215	1300	1	2750
C19	1095	6250	525	55	7.5	230	1125	ND	775
K20	1590	6665	780	80	10.5	ND	1800	1	1340
H23	900	5000	365	70	6	ND	925	ND	725
TW27	1190	8165	565	60	7.5	425	1300	ND	2300
BY28	1325	11750	700	70	8	320	1550	ND	3700
PI30	1190	10650	550	70	10	355	1300	1	5000
station	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1A94	1350	10482	693	75	10.5	340	1450	1.5	1813
TC6	1180	7165	665	75	9	ND	1450	ND	1375
TC8	1250	8000	550	70	8	105	1400	ND	1400
TC9	1005	6165	635	60	8	ND	1250	ND	1950
P10	1875	16850	1085	165	17	250	2500	1.5	5275
PC13	1335	10000	685	125	8	250	1625	1	2625
CY16	1150	7335	615	80	6	175	1500	1	3625
C19	1055	6500	475	50	6.25	70	975	ND	1025
K20	950	5500	450	55	5.5	70	1075	1	1375
H23	685	2665	265	40	6	ND	675	ND	730
TW27	1400	13000	715	80	7	250	1500	1	3875
BY28	1650	16500	850	135	11	285	1775	ND	5000
PI30	1315	10250	585	80	6.5	355	1500	1	7000
station	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1A95	1125	6833	615	80	5.75	213	1275	ND	3075
TC6	1050	5835	565	70	8	ND	1125	ND	1775
TC8	1175	7000	600	75	7.5	ND	1300	ND	3100
TC9	1450	11250	735	105	8.5	70	1500	1	3875
P10	1425	13200	650	135	12	320	1625	1	4300
PC13	950	6665	400	100	6.5	ND	825	1	3250
CY16	1380	11750	735	115	11.5	175	1500	1.5	7250
C19	1433	9625	775	100	12	268	1563	1	3100
K20	1450	10740	750	105	13	355	1550	1	3350
H23	1400	10000	700	95	11	215	1500	ND	3550
TW27	1365	14260	615	90	10	285	1325	ND	5300
BY28	950	7500	450	75	8	145	975	ND	5250
PI30	1040	9000	450	75	7.5	175	1025	ND	4375
station	Al	Fe	Cu	Pb	Ni	As	Zn	Cd	Ca
D1A96	1350	10375	683	100	14.25	250	1363	ND	3938
TC6	935	5150	435	55	6.5	105	900	ND	1200
TC8	1120	7500	550	70	7.5	175	1050	ND	2250
TC9	1160	8250	515	65	9	145	1100	ND	2325
P10	1135	9250	535	160	8	285	1000	1	5300
PC13	1350	12500	615	160	12.5	215	1200	1	4600
CY16	1105	7650	500	85	9	250	1150	ND	5000
C19	1505	11125	910	110	16.75	355	1825	ND	4875
K20	1155	7350	550	75	8.5	175	1075	ND	3050
H23	990	6150	500	60	8	70	875	ND	2625
TW27	980	6850	435	65	6.5	175	850	ND	4625
BY28	1150	8600	650	95	14	285	1200	ND	7750
PI30	910	6150	365	65	8	105	800	1	4575

Note: ND denotes not detected

Appendix 1.1c: Restronguet Creek, mean sediment metal concentrations								
STATION	Al	Fe	Cu	Pb	Ni	As	Zn	Ca
D1	1192	7870	622	71	9	221	1333	2505
TC6	1095	5730	653	70	9	105	1375	1750
TC8	964	5767	470	57	6	152	1005	1970
TC9	1028	6630	547	67	8	141	1155	2250
P10	1455	12327	814	149	13	307	1800	4560
PC13	1032	7966	493	110	8	214	1065	2665
CY16	1167	8481	620	86	8	206	1345	4105
C19	1283	8500	666	76	10	231	1443	2230
K20	1339	7984	716	80	9	230	1470	1993
H23	931	5563	459	65	7	130	955	1826
TW27	1196	9785	596	74	8	284	1285	3980
BY28	1213	10570	653	91	10	271	1420	5240
PI30	1109	9143	520	76	8	248	1185	6090
St Clements	1643	8974	154	84	6	ND	55	2000

Appendix 1.2: The Erme Estuary, sediment geochemical data								
station	Al	Fe	Cu	Pb	Ni	Zn	Cd	Ca
F1A93	630	2380	6.5	40	3	49	1	850
HP2	700	3015	9.5	45	4.5	95	ND	1300
HP3	865	3650	12	55	3.5	125	1	1400
HP4	630	2700	10.5	40	5	175	0.5	600
E5	665	2700	9.5	35	5	53	ND	1100
E6	1125	5350	15.5	65	8	150	1.5	1750
E7	530	3015	11	40	6.5	59	1	14800
E8	500	2780	9	30	7.5	50	1	14950
E9	410	2335	8.5	30	5	59	ND	13050
E10	330	1905	6.5	30	4	35	ND	10850
OW11	480	2475	8	35	5	43	ND	11900
OW12	365	2065	6	25	2.5	36	1	10850
OW14	725	4165	9.5	45	7	52	1	17400
OW15	725	4500	10.5	45	11	58	ND	15650
CM16	940	6800	15	55	15	85	0.5	8100
CM17	850	6500	15	50	7.5	75	0.5	5900
S18	900	700	14.5	50	10	62	1	6350
S19	575	4000	10	35	6	70	1	17850
S20	560	4000	8	32.5	5.75	55	1.5	20575
MEAN	658.2	3422.9	10.3	41.2	6.4	72.9	1.0	9222.4

Appendix 1.3: The Fowey Estuary, sediment geochemical data								
station	Al	Fe	Cu	Pb	Ni	Zn	Cd	Ca
StW1A94	175	745	33.5	5	ND	120	ND	105
StW2	230	950	13.5	10	1.5	25	ND	150
LPO3	215	1205	52.5	15	3	115	ND	143
RC4	240	1335	22.5	10	ND	45	ND	3000
CH5	490	2380	80.5	25	3	180	ND	5000
CH6	275	1125	72.5	15	ND	175	ND	2500
PM7	525	3415	140	40	7.5	310	1	9250
MP9	300	1270	87.5	30	4	210	ND	2250
MP10	275	985	76.5	20	4.5	170	ND	2000
PPH11	370	1745	72.5	25	1.5	210	ND	1550
G12	55	240	11	10	ND	20	ND	122
G13	513	2073	40	27.5	4.75	85	1.5	3175
G14	175	875	18	25	ND	31.5	ND	1550
MEAN	295.2	1411.0	55.4	19.8	3.7	130.5	1.3	2368.8

Appendix 1.4: The Avon Estuary, sediment geochemical data								
station	Al	Fe	Cu	Pb	Ni	Zn	Cd	Ca
A1A95	415	2380	10.5	20	5	34	ND	3050
A2	600	2475	18	20	5	50	ND	3500
A3	350	1745	9	15	ND	27	ND	1550
A4	300	1510	3	15	2	15	ND	1200
A5	700	2855	9.5	25	5	38.5	ND	6100
A6	455	2220	15	20	2.5	40	ND	4800
A7	525	2700	62	25	3.5	150	ND	2600
A8	440	2220	14	25	5	42.5	ND	6350
A9	450	1620	12.5	15	5	41	ND	1300
A10	435	2220	12.5	15	3	35	ND	5650
A11	590	3095	18	30	5	47.5	ND	2600
A12	600	3058	14.5	14.5	7.5	47	ND	15925
MEAN	488.3	2341.5	16.5	20.0	4.4	47.3	ND	4552.1

Note: ND denotes not detected

2.1 Restronguet Creek

D1/Autumn 92	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	81	52	8	10	5
E.Williamsoni	76	48	3	3.9	2
A.beccarii	0	0	0	0	0
TOTAL	157	100	11		7
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	224	44	36	16	7
E.Williamsoni	288	56	24	8	5
A.beccarii	0	0	0	0	0
TOTAL	512	100	60		12
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	144	34	5	3	1
E.Williamsoni	278	65	10	4	2
A.beccarii	5	1.2	0	0	0
TOTAL	427	100.2	15		3
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	430	59	34	8	5
E.Williamsoni	288	39	20	7	3
A.beccarii	16	2	0	0	0
TOTAL	734	100	54		8
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	332	36	48	14	5
E.Williamsoni	560	60	24	4	3
A.beccarii	40	4	32	80	3
TOTAL	932	100	104		11
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	360	37.3	8	2	1
E.Williamsoni	588	60.5	12	2	1
A.beccarii	24	2	0	0	0
TOTAL	972	99.8	20		2
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	36	26	8	22	6
E.Williamsoni	100	71	8	8	6
A.beccarii	4	3	0	0	0
TOTAL	140	100	16		12
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	624	49	31	5	2
E.Williamsoni	592	46	4	1	0.3
A.beccarii	64	5	0	0	0
TOTAL	1280	100	35		2
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	792	28	64	8	2
E.Williamsoni	1968	69	112	6	4
A.beccarii	96	3	0	0	0
TOTAL	2856	100	176		6

D1/Winter 93	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	392	83	36	9	8
E.Williamsoni	78	17	12	15	3
A.beccarii	0	0	0	0	0
TOTAL	470	100	48		11
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	740	66	20	3	2
E.Williamsoni	377	34	19	5	2
A.beccarii	0	0	0	0	0
TOTAL	1117	100	39		4
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	236	38	24	10	4
E.Williamsoni	374	61	17	5	3
A.beccarii	8	1	0	0	0
TOTAL	618	100	41		7
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1281	84	48	4	3
E.Williamsoni	188	12	0	0	0
A.beccarii	64	4	16	25	3
TOTAL	1533	100	64		6
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	532	57	16	3	2
E.Williamsoni	408	43	24	6	3
A.beccarii	0	0	0	0	0
TOTAL	940	100	40		5
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	376	47	0	0	0
E.Williamsoni	392	49	24	6	3
A.beccarii	32	4	0	0	0
TOTAL	800	100	24		3
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	228	61	8	4	2
E.Williamsoni	104	28	4	4	1
A.beccarii	40	11	0	0	0
TOTAL	372	100	12		3
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	224	49	8	4	2
E.Williamsoni	120	26	32	27	7
A.beccarii	112	25	0	0	0
TOTAL	456	100	40		9
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	408	51.5	16	4	2
E.Williamsoni	380	48	2	1	0.3
A.beccarii	4	0.5	0	0	0
TOTAL	792	100	18		2

D1/Spring 93	SC/T	%T	DSC/T	% Sp	%T
H.germanica	80	89	10	13	11
E.Williamsoni	10	11	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	90	100	10		11
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	120	100	25	21	21
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	120	100	25	21	21
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2030	95.5	240	12	11
E.Williamsoni	60	3	20	33	1
A.beccarii	30	1.5	0	0	0
TOTAL	2120	100	260		12
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1280	96	170	13	13
E.Williamsoni	45	3.4	10	22	1
A.beccarii	5	0.4	0	0	0
TOTAL	1330	99.8	180		14
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2973	94	100	3	3
E.Williamsoni	137	4.5	10	7	0
A.beccarii	40	1.3	0	0	0
TOTAL	3150	99.8	110		3
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	874	91	42	5	4
E.Williamsoni	58	6	6	10	1
A.beccarii	28	3	0	0	0
TOTAL	960	100	48		5
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2180	91	64	3	3
E.Williamsoni	112	5	0	0	0
A.beccarii	88	4	4	5	0.2
TOTAL	2380	100	68		3
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	245	100	25	10	10
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	245	100	25		10
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	162	88	4	2	2
E.Williamsoni	23	12	3	13	2
A.beccarii	0	0	0	0	0
TOTAL	185	100	7		4
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3360	94.4	96	3	3
E.Williamsoni	120	3.6	12	10	0
A.beccarii	64	2	0	0	0
TOTAL	3544	100	108		3
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4552	97	188	4	4
E.Williamsoni	112	2	8	7	0.2
A.beccarii	52	1	4	8	0.1
TOTAL	4716	100	200		4.3
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	7900	84	120	2	1
E.Williamsoni	320	3	16	5	0.2
A.beccarii	1224	13	56	5	0.6
TOTAL	9444	100	192		2

D1/Summer 93	SC/T	%T	DSC/T	% Sp	%T
H.germanica	28	61	0	0	0
E.Williamsoni	10	22	0	0	0
A.beccarii	8	17	0	0	0
TOTAL	46	100	0		0
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1346	78	136	10	8
E.Williamsoni	338	20	28	8	1.6
A.beccarii	46	2	4	9	0.2
TOTAL	1730	100	168		10
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3388	97	236	7	7
E.Williamsoni	56	2	0	0	0
A.beccarii	44	1	8	18	0.2
TOTAL	3488	100	244		7
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	672	82	56	8	7
E.Williamsoni	124	15	4	3	0.5
A.beccarii	24	3	0	0	0
TOTAL	820	100.2	60		7.5
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1448	80	106	7	6
E.Williamsoni	254	14	40	16	2.2
A.beccarii	108	6	8	7	0.4
TOTAL	1810	100	154		8.6
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	328	95.4	4	1	1
E.Williamsoni	8	2.3	0	0	0
A.beccarii	8	2.3	0	0	0
TOTAL	344	100	4		1
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1440	73	32	2	2
E.Williamsoni	460	23	20	4	1
A.beccarii	76	4	20	26	1
TOTAL	1976	100	72		4
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	18	100	10	56	56
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	18	100	10		56
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	34	63	18	53	33
E.Williamsoni	20	37	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	54	100	18		33
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2232	82	104	5	4
E.Williamsoni	384	14	0	0	0
A.beccarii	96	4	0	0	0
TOTAL	2712	100	104		4
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1712	88	152	9	8
E.Williamsoni	184	10	4	2	0.2
A.beccarii	32	2	0	0	0
TOTAL	1928	100	156		8.2
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2774	80	78	3	2
E.Williamsoni	376	11	22	6	0.6
A.beccarii	308	9	40	13	1.2
TOTAL	3458	100	76		3.8

D1/Autumn 93	SC/T	%T	DSC/T	% Sp	%T
H.germanica	32	44	8	25	11
E.Williamsoni	9	12	0	0	0
A.beccarii	32	44	0	0	0
TOTAL	73	100	8		11
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	138	77	42	30	23
E.Williamsoni	42	23	12	29	7
A.beccarii	0	0	0	0	0
TOTAL	180	100	54		30
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	202	67	12	6	4
E.Williamsoni	100	33	8	8	3
A.beccarii	0	0	0	0	0
TOTAL	302	100	20		7
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	128	50	24	19	9.4
E.Williamsoni	128	50	8	6	3.1
A.beccarii	0	0	0	0	0
TOTAL	256	100	32		13
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	137	40	9	7	3
E.Williamsoni	159	47	4	3	1.2
A.beccarii	44	13	0	0	0
TOTAL	340	100	13		4
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	33	44	4	12	5
E.Williamsoni	41	56	7	17	9.5
A.beccarii	0	0	0	0	0
TOTAL	74	100	11		15
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	90	28	6	7	2
E.Williamsoni	106	32	8	8	2.4
A.beccarii	132	40	0	0	0
TOTAL	328	100	14		4
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	0	0	0	0	0
E.Williamsoni	6	100	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	6	100	0		0
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	0	0	0	0	0
E.Williamsoni	8	100	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	8	100	0		0
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	164	58	52	32	18
E.Williamsoni	120	42	12	10	4
A.beccarii	0	0	0	0	0
TOTAL	284	100	64		22
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	284	38	0	0	0
E.Williamsoni	344	46	24	7	3
A.beccarii	120	16	0	0	0
TOTAL	748	100	24		3
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1164	57	136	12	7
E.Williamsoni	436	22	20	5	1
A.beccarii	432	21	0	0	0
TOTAL	2032	100	156		8

D1/Winter 94	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	104	36	0	0	0
E.Williamsoni	42	14	2	5	1
A.beccarii	146	50	0	0	0
TOTAL	292	100	2		1
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	206	74	38	18	14
E.Williamsoni	72	26	1	1	0.4
A.beccarii	0	0	0	0	0
TOTAL	278	100	39		14.4
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	186	63	5	3	2
E.Williamsoni	110	37	4	4	1
A.beccarii	0	0	0	0	0
TOTAL	296	100	9		3
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	137	87	0	0	0
E.Williamsoni	21	13	1	5	1
A.beccarii	0	0	0	0	0
TOTAL	158	100	1		1
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	20	62.5	0	0	0
E.Williamsoni	12	37.5	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	32	100	0		0
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	40	25	0	0	0
E.Williamsoni	91	55	12	13	7
A.beccarii	32	20	0	0	0
TOTAL	163	100	12		7
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	940	57.5	28	3	2
E.Williamsoni	636	39	69	11	4.2
A.beccarii	60	3.5	0	0	0
TOTAL	1636	100	97		6
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	182	50	36	20	10
E.Williamsoni	174	48	10	6	2.8
A.beccarii	6	2	0	0	0
TOTAL	362	100	14		13
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	376	40	12	3	1
E.Williamsoni	488	52	48	10	5.1
A.beccarii	72	8	4	6	0.4
TOTAL	936	100	64		6.5

D1/Spring 94	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4	100	0	0	0
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	4	100	0		0
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	16	76	2	13	10
E.Williamsoni	5	24	2	40	9.5
A.beccarii	0	0	0	0	0
TOTAL	21	100	4		19.5
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	10	100	2	20	20
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	10	100	2		20
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	225	99	14	6	6
E.Williamsoni	1	1	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	226	100	14		6
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	496	99	66	13	13
E.Williamsoni	6	1	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	502	100	66		13
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	392	78	32	8	6
E.Williamsoni	96	19	24	25	4.8
A.beccarii	16	3	0	0	0
TOTAL	504	100	56		11
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica					
E.Williamsoni					
A.beccarii					
TOTAL					
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1000	99	132	13	13
E.Williamsoni	4	0.5	4	100	0.4
A.beccarii	4	0.5	0	0	0
TOTAL	1008	100	136		13.4
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	280	85	14	5	4
E.Williamsoni	42	13	12	29	3.7
A.beccarii	6	2	0	0	0
TOTAL	328	100	26		8
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1588	97	52	3	3
E.Williamsoni	40	2	0	0	0
A.beccarii	12	1	0	0	0
TOTAL	1640	100	52		3

D1/Summer 94	SC/T	%T	DSC/T	% Sp	%T
H.germanica	261	86	20	8	6.6
E.Williamsoni	38	13	2	5	0.7
A.beccarii	4	1	0	0	0
TOTAL	303	100	22		7.3
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	728	81	58	8	6
E.Williamsoni	168	18.6	0	0	0
A.beccarii	4	0.4	0	0	0
TOTAL	902	100	58		6
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1680	76	116	7	5
E.Williamsoni	504	23	16	3	1
A.beccarii	16	1	0	0	0
TOTAL	2200	100	132		6
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	880	79	72	8	7
E.Williamsoni	232	21	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	1112	100	72		7
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	624	82	60	10	8
E.Williamsoni	124	16	8	6	1
A.beccarii	16	2	0	0	0
TOTAL	764	100	68		9
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	700	71	44	6	5
E.Williamsoni	267	27	4	1	0
A.beccarii	16	2	0	0	0
TOTAL	983	100	48		5
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1192	54	16	1	1
E.Williamsoni	792	36	0	0	0
A.beccarii	232	10	0	0	0
TOTAL	2216	100	16		1
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	500	58	82	16	9.5
E.Williamsoni	364	42	12	3	1.4
A.beccarii	0	0	0	0	0
TOTAL	864	100	94		10.9
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	No data		No data		
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	158	51	12	8	4
E.Williamsoni	152	49	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	310	100	12		4
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1352	60	56	4	2.5
E.Williamsoni	880	38	8	1	0
A.beccarii	56	2	0	0	0
TOTAL	2288	100	64		2.5
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1472	48	80	5	2.6
E.Williamsoni	1608	51	16	1	0.5
A.beccarii	16	1	0	0	0
TOTAL	3096	100	96		3
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1536	40	48	3	1
E.Williamsoni	2232	57	48	2	1
A.beccarii	120	3	0	0	0
TOTAL	3888	100	96		2

D1/Autumn 94	SC/T	%T	DSC/T	% Sp	%T
H.germanica	40	6	0	0	0
E.Williamsoni	586	94	18	3	3
A.beccarii	0	0	0	0	0
TOTAL	626	100	18		3
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	240	12	8	3	0
E.Williamsoni	1688	87	96	6	5
A.beccarii	16	1	0	0	0
TOTAL	1944	100	104		5
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	96	12	0	0	0
E.Williamsoni	688	87	56	8	7
A.beccarii	4	1	0	0	0
TOTAL	788	100	56		7
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	224	13	0	0	0
E.Williamsoni	1536	85	120	8	7
A.beccarii	32	2	0	0	0
TOTAL	1792	100	120		7
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	114	36	4	4	1
E.Williamsoni	198	63	12	6	4
A.beccarii	4	1	0	0	0
TOTAL	316	100	16		5
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	200	19	4	2	0
E.Williamsoni	848	78	76	9	7
A.beccarii	36	3	0	0	0
TOTAL	1084	100	80		7
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	184	10	0	0	0
E.Williamsoni	1592	85	88	6	5
A.beccarii	96	5	0	0	0
TOTAL	1872	100	88		5
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	72	26	4	6	1
E.Williamsoni	202	74	2	1	1
A.beccarii	0	0	0	0	0
TOTAL	274	100	6		2
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	8	15	0	0	0
E.Williamsoni	44	85	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	52	100	0		0
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4	1	2	50	0
E.Williamsoni	670	99	40	6	6
A.beccarii	0	0	0	0	0
TOTAL	674	100	42		6
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	128	8	0	0	0
E.Williamsoni	1432	92	104	7	7
A.beccarii	0	0	0	0	0
TOTAL	1560	100	104		7
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	120	31	0	0	0
E.Williamsoni	224	57	24	11	6
A.beccarii	48	12	0	0	0
TOTAL	392	100	24		6
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	96	22	0	0	0
E.Williamsoni	336	78	24	7	6
A.beccarii	0	0	0	0	0
TOTAL	432	100	24		6

D1/Winter 95	SC/T	%T	DSC/T	% Sp	%T
H.germanica	32	11	0	0	0
E.Williamsoni	252	89	36	14	13
A.beccarii	0	0	0	0	0
TOTAL	284	100	36		13
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	112	11	0	0	0
E.Williamsoni	872	87	64	7	6
A.beccarii	16	2	0	0	0
TOTAL	1000	100	64		6
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	8	2	0	0	0
E.Williamsoni	384	98	32	8	8
A.beccarii	0	0	0	0	0
TOTAL	392	100	32		8
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	160	27	0	0	0
E.Williamsoni	432	73	40	9	7
A.beccarii	0	0	0	0	0
TOTAL	592	100	40		7
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	72	82	0	0	0
E.Williamsoni	0	0	0	0	0
A.beccarii	16	18	0	0	0
TOTAL	88	100	0		0
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	8	20	0	0	0
E.Williamsoni	32	80	8	25	20
A.beccarii	0	0	0	0	0
TOTAL	40	100	8		20
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	224	57	0	0	0
E.Williamsoni	152	39	16	11	4
A.beccarii	16	4	0	0	0
TOTAL	392	100	16		4
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	No data		No data		
E.Williamsoni					
A.beccarii					
TOTAL					
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	No data		No data		
E.Williamsoni					
A.beccarii					
TOTAL					
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	No data		No data		
E.Williamsoni					
A.beccarii					
TOTAL					
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	264	30	16	6	2
E.Williamsoni	528	61	32	6	4
A.beccarii	80	9	0	0	0
TOTAL	872	100	48		6
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	128	21	8	6	1
E.Williamsoni	440	74	16	4	3
A.beccarii	32	5	0	0	0
TOTAL	600	100	24		4
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	680	21	24	4	1
E.Williamsoni	2480	76	208	8	6
A.beccarii	120	3	0	0	0
TOTAL	3280	100	232		7

D1/Spring 95	SC/T	%T	DSC/T	% Sp	%T
H.germanica	40	93	1	3	2
E.Williamsoni	2	5	0	0	0
A.beccarii	1	2	0	0	0
TOTAL	43	100	1		2
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	88	44	36	41	18
E.Williamsoni	114	56	12	11	6
A.beccarii	0	0	0	0	0
TOTAL	202	100	48		24
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	264	58	24	9	5.3
E.Williamsoni	188	42	20	11	4.4
A.beccarii	0	0	0	0	0
TOTAL	452	100	44		10
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	432	46	16	4	2
E.Williamsoni	504	54	72	14	8
A.beccarii	0	0	0	0	0
TOTAL	936	100	88		10
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	979	96	72	7	7
E.Williamsoni	32	3	8	25	1
A.beccarii	4	0.4	0	0	0
TOTAL	1015	99.4	80		8
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	724	96	8	1	1
E.Williamsoni	28	4	2	7	0
A.beccarii	0	0	0	0	0
TOTAL	752	100	10		1
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	5728	91	144	3	2
E.Williamsoni	520	8	32	6	1
A.beccarii	80	1	80	100	1
TOTAL	6328	100	256		4
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	108	95	0	0	0
E.Williamsoni	5	5	4	80	4
A.beccarii	0	0	0	0	0
TOTAL	113	100	4		4
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	70	100	0	0	0
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	70	100	0		0
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4	100	4	100	100
E.Williamsoni	0	0	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	4	100	4		100
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3200	97	60	2	2
E.Williamsoni	48	1	0	0	0
A.beccarii	56	2	0	0	0
TOTAL	3304	100	60		2
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2300	87	56	2	2
E.Williamsoni	280	11	4	1	0
A.beccarii	56	2	0	0	0
TOTAL	2636	100	60		2
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1984	84	0	0	0
E.Williamsoni	320	13	48	15	2
A.beccarii	72	3	0	0	0
TOTAL	2376	100	48		2

D1/Summer 95	SC/T	%T	DSC/T	% Sp	%T
H.germanica	980	54	56	6	3
E.Williamsoni	804	44	36	4	2
A.beccarii	28	2	0	0	0
TOTAL	1812	100	92		5
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	716	60	16	2	1
E.Williamsoni	392	33	8	2	1
A.beccarii	80	7	16	20	1
TOTAL	1188	100	40		3
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3056	73	64	2	2
E.Williamsoni	1144	27	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	4200	100	64		2
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2384	75	136	6	4
E.Williamsoni	788	24.5	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	3172	100	136		4
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	666	48	24	4	2
E.Williamsoni	708	51.3	24	3	2
A.beccarii	8	0.6	0	0	0
TOTAL	1382	100	48		4
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3112	54	120	4	2
E.Williamsoni	2584	44	56	2	1
A.beccarii	104	2.1	16	15	0.3
TOTAL	5800	100	192		3
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	13232	57	144	1	1
E.Williamsoni	9568	41.5	96	1	0
A.beccarii	176	1.2	0	0	0
TOTAL	22976	100	240		1
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	160	25	34	21	5
E.Williamsoni	476	74.5	4	1	1
A.beccarii	4	0.6	0	0	0
TOTAL	640	100	38		6
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	168	31	72	43	13
E.Williamsoni	374	68	14	4	3
A.beccarii	4	1	0	0	0
TOTAL	546	100	86		16
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1216	52	24	2	1
E.Williamsoni	1112	48	64	6	3
A.beccarii	0	0	0	0	0
TOTAL	2328	100	88		4
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2896	72	104	4	3
E.Williamsoni	1104	27	16	1	0
A.beccarii	16	0.4	0	0	0
TOTAL	4016	100	120		3
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	3168	53	48	2	1
E.Williamsoni	2400	41	32	1	1
A.beccarii	336	6	16	5	0.3
TOTAL	5904	100	96		2
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4576	46	80	2	1
E.Williamsoni	5136	51	32	1	0
A.beccarii	336	3.3	0	0	0
TOTAL	10048	100	112		1

D1/Autumn 95	SC/T	%T	DSC/T	% Sp	%T
H.germanica	18	7	0	0	0
E.Williamsoni	172	59	2	1	1
A.beccarii	96	34	0	0	0
TOTAL	286	100	2		1
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	56	5	8	14	1
E.Williamsoni	808	78	88	11	8
A.beccarii	176	17	0	0	0
TOTAL	1040	100	96		9
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	80	10	0	0	0
E.Williamsoni	616	70	16	3	2
A.beccarii	176	20	16	9	2
TOTAL	872	100	32		4
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	32	4	0	0	0
E.Williamsoni	832	96	32	4	4
A.beccarii	0	0	0	0	0
TOTAL	864	100	32		4
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	48	10.5	0	0	0
E.Williamsoni	360	79	0	0	0
A.beccarii	48	10.5	16	33	4
TOTAL	456	100	16		4
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	24	1	0	0	0
E.Williamsoni	1632	87	120	7	6
A.beccarii	240	12	0	0	0
TOTAL	1896	100	120		6
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	528	36	0	0	0
E.Williamsoni	732	49	32	4	2
A.beccarii	220	15	0	0	0
TOTAL	1480	100	32		2
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	24	4	0	0	0
E.Williamsoni	528	96	48	9	9
A.beccarii	0	0	0	0	0
TOTAL	552	100	48		9
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	12	8	0	0	0
E.Williamsoni	146	92	4	3	3
A.beccarii	0	0	0	0	0
TOTAL	158	100	4		3
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	344	16	0	0	0
E.Williamsoni	1464	66	96	7	4
A.beccarii	384	18	0	0	0
TOTAL	2192	100	96		4
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	56	4	0	0	0
E.Williamsoni	568	40	72	13	5
A.beccarii	800	56	48	6	3
TOTAL	1424	100	120		8
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	168	4	16	10	0
E.Williamsoni	1048	26	128	12	3
A.beccarii	2752	70	32	1	1
TOTAL	3968	100	166		4
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	144	6	0	0	0
E.Williamsoni	1888	74	64	3	3
A.beccarii	504	20	16	3	1
TOTAL	2536	100	80		4

D1/Winter 96	SC/T	%T	DSC/T	% Sp	%T
H.germanica	0	0	0	0	0
E.Williamsoni	8	100	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	8	100	0		0
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	82	28	16	20	5
E.Williamsoni	116	39	8	7	3
A.beccarii	96	33	0	0	0
TOTAL	294	100	24		8
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	80	22	0	0	0
E.Williamsoni	280	78	8	3	2
A.beccarii	0	0	0	0	0
TOTAL	360	100	8		2
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	128	26	0	0	0
E.Williamsoni	200	41	0	0	0
A.beccarii	160	33	0	0	0
TOTAL	488	100	0		0
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	4	3	0	0	0
E.Williamsoni	0	0	0	0	0
A.beccarii	128	97	0	0	0
TOTAL	132	100	0		0
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	16	18	0	0	0
E.Williamsoni	20	22	0	0	0
A.beccarii	52	60	0	0	0
TOTAL	88	100	0		0
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	144	10	0	0	0
E.Williamsoni	644	44.5	68	11	5
A.beccarii	656	45	16	2	1
TOTAL	1444	99.5	84		6
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	32	29.5	0	0	0
E.Williamsoni	45	41	5	11	5
A.beccarii	32	29.5	0	0	0
TOTAL	109	100	5		5
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	0	0	0	0	0
E.Williamsoni	0	0	0	0	0
A.beccarii	9	100	0	0	0
TOTAL	9	100	0		0
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	64	15	0	0	0
E.Williamsoni	344	81	0	0	0
A.beccarii	16	4	0	0	0
TOTAL	424	100	0		0
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	304	4	32	11	0.5
E.Williamsoni	2848	44	208	7	3
A.beccarii	3376	52	144	4	2
TOTAL	6528	100	384		5.5
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	486	14	16	3	0.5
E.Williamsoni	1384	41	66	5	2
A.beccarii	1506	45	32	2	1
TOTAL	3376	100	114		3.5
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	16	12	0	0	0
E.Williamsoni	112	88	0	0	0
A.beccarii	0	0	0	0	0
TOTAL	128	100	0		0

D1/Spring 96	SC/T	%T	DSC/T	% Sp	%T
H.germanica	129	79	19	15	11.6
E.Williamsoni	27	16	8	30	5
A.beccarii	8	5	1	13	0.6
TOTAL	164	100	28		17
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2606	87	170	7	6
E.Williamsoni	312	10	18	6	1
A.beccarii	88	3	4	5	0.1
TOTAL	3006	100	192		7
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1400	85	44	3	3
E.Williamsoni	112	7	0	0	0
A.beccarii	136	8	16	12	1
TOTAL	1648	100	60		4
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1876	85	148	8	7
E.Williamsoni	148	7	16	11	1
A.beccarii	184	8	32	17	1
TOTAL	2208	100	196		9
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1210	84	17	1	1
E.Williamsoni	166	12	1	1	0
A.beccarii	64	4	0	0	0
TOTAL	1440	100	18		1
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	342	75	2	1	0.4
E.Williamsoni	108	24	4	4	1
A.beccarii	4	1	0	0	0
TOTAL	454	100	6		1.4
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1856	79	88	5	4
E.Williamsoni	224	9	48	21	2
A.beccarii	280	12	40	14	2
TOTAL	2360	100	176		8
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	82	56	1	1	1
E.Williamsoni	15	11	2	13	1
A.beccarii	48	33	0	0	0
TOTAL	145	100	3		2
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	52	85	0	0	0
E.Williamsoni	7	12	1	14	2
A.beccarii	2	3	0	0	0
TOTAL	61	100	1		2
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	184	84	4	2	2
E.Williamsoni	20	9	0	0	0
A.beccarii	16	7	0	0	0
TOTAL	220	100	4		2
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	2032	79	48	2	2
E.Williamsoni	208	8	32	15	1
A.beccarii	336	13	0	0	0
TOTAL	2576	100	80		3
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1984	69	24	1	1
E.Williamsoni	96	3	0	0	0
A.beccarii	808	28	72	9	2
TOTAL	2888	100	96		3
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	304	59	8	3	2
E.Williamsoni	96	19	24	25	5
A.beccarii	112	22	0	0	0
TOTAL	512	100	32		7

D1/Summer 96	SC/T	%T	DSC/T	% Sp	%T
H.germanica	**2612**	63	**184**	7	5
E.Williamsoni	**1192**	29	**40**	3	1
A.beccarii	**336**	8	**48**	14	1
TOTAL	**4144**	100	**272**		7
TC6	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**2240**	69	**240**	11	7
E.Williamsoni	**824**	25	**0**	0	0
A.beccarii	**200**	6	**8**	4	0.2
TOTAL	**3264**	100	**248**		7
TC8	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1144**	40	**56**	5	2
E.Williamsoni	**1320**	46	**0**	0	0
A.beccarii	**392**	14	**32**	8	1
TOTAL	**2856**	100	**88**		3
TC9	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**2000**	46	**120**	6	3
E.Williamsoni	**2208**	50	**0**	0	0
A.beccarii	**192**	4	**0**	0	0
TOTAL	**4400**	100	**120**		3
P10	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**2848**	42	**160**	6	2
E.Williamsoni	**2912**	44	**64**	2	1
A.beccarii	**960**	14	**64**	7	1
TOTAL	**6720**	100	**288**		4
PC13	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1440**	34	**136**	9	3
E.Williamsoni	**2552**	61	**8**	0	0
A.beccarii	**240**	5	**0**	0	0
TOTAL	**4232**	100	**144**		3
CY16	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**2048**	35	**64**	3	1
E.Williamsoni	**3184**	54	**32**	1	1
A.beccarii	**672**	11	**48**	7	1
TOTAL	**5904**	100	**144**		3
C19	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1132**	59	**196**	17	10
E.Williamsoni	**648**	33	**38**	6	2
A.beccarii	**146**	8	**32**	22	2
TOTAL	**1926**	100	**266**		14
K20	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1400**	79	**44**	3	2.5
E.Williamsoni	**312**	17.8	**16**	5	1
A.beccarii	**64**	3.8	**0**	0	0
TOTAL	**1776**	100.6	**60**		3.5
H23	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**360**	19	**36**	10	2
E.Williamsoni	**1404**	76	**0**	0	0
A.beccarii	**88**	5	**24**	27	1
TOTAL	**1852**	100	**60**		3
TW27	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1632**	25	**80**	5	1
E.Williamsoni	**4544**	67	**48**	1	1
A.beccarii	**496**	8	**0**	0	0
TOTAL	**6672**	100	**128**		2
BY28	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1296**	34	**48**	4	1
E.Williamsoni	**1744**	47	**0**	0	0
A.beccarii	**704**	19	**0**	0	0
TOTAL	**3744**	100	**48**		1
PI30	**SC/T**	%T	**DSC/T**	% Sp	%T
H.germanica	**1088**	32	**0**	0	0
E.Williamsoni	**1376**	41	**16**	1	0.5
A.beccarii	**896**	27	**64**	7	2
TOTAL	**3360**	100	**80**		2.5

D1/Autumn 96	SC/T	%T	DSC/T	% Sp	%T
H.germanica	185	16	3	2	0
E.Williamsoni	945	81	25	3	2
A.beccarii	32	3	0	0	0
TOTAL	1162	100	28		2
TC6	SC/T	%T	DSC/T	% Sp	%T
H.germanica	296	16	0	0	0
E.Williamsoni	1492	79	64	4	3
A.beccarii	100	5	0	0	0
TOTAL	1888	100	64		3
TC8	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1240	17	64	5	1
E.Williamsoni	5672	78	136	2	2
A.beccarii	328	5	72	22	1
TOTAL	7240	100	272		4
TC9	SC/T	%T	DSC/T	% Sp	%T
H.germanica	204	11.3	0	0	0
E.Williamsoni	1508	83.4	12	1	1
A.beccarii	96	5.3	0	0	0
TOTAL	1808	100	12		1
P10	SC/T	%T	DSC/T	% Sp	%T
H.germanica	162	25	0	0	0
E.Williamsoni	394	62	0	0	0
A.beccarii	80	13	0	0	0
TOTAL	636	100	0		0
PC13	SC/T	%T	DSC/T	% Sp	%T
H.germanica	206	19.4	0	0	0
E.Williamsoni	802	75.4	42	5	4
A.beccarii	56	5.3	0	0	0
TOTAL	1064	100	42		4
CY16	SC/T	%T	DSC/T	% Sp	%T
H.germanica	304	12.8	0	0	0
E.Williamsoni	1824	76.5	0	0	0
A.beccarii	256	10.7	0	0	0
TOTAL	2384	100	0		0
C19	SC/T	%T	DSC/T	% Sp	%T
H.germanica	28	17.5	0	0	0
E.Williamsoni	132	82.5	8	6	5
A.beccarii	0	0	0	0	0
TOTAL	160	100	8		5
K20	SC/T	%T	DSC/T	% Sp	%T
H.germanica	64	12	12	19	2
E.Williamsoni	390	75	12	3	2
A.beccarii	68	13	0	0	0
TOTAL	522	100	24		4
H23	SC/T	%T	DSC/T	% Sp	%T
H.germanica	136	3	0	0	0
E.Williamsoni	3832	92	152	4	4
A.beccarii	200	5	0	0	0
TOTAL	4168	100	152		4
TW27	SC/T	%T	DSC/T	% Sp	%T
H.germanica	832	27	0	0	0
E.Williamsoni	1744	57	96	6	3
A.beccarii	480	16	30	6	1
TOTAL	3056	100	126		4
BY28	SC/T	%T	DSC/T	% Sp	%T
H.germanica	336	11	0	0	0
E.Williamsoni	2512	84	32	1	1
A.beccarii	160	5	0	0	0
TOTAL	3008	100	32		1
PI30	SC/T	%T	DSC/T	% Sp	%T
H.germanica	1088	46	0	0	0
E.Williamsoni	1024	43	64	6	3
A.beccarii	256	11	0	0	0
TOTAL	2368	100	64		3

F1/Winter 93	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
HP2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
HP3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	988	100	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	988		0		0	0
HP4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	2	1	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	253	99	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	255		0		0	0
E5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	392	12.6	21	5	1	5
A.beccarii	0	0	0	0	0	0
M.fusca	2692	87	0	0	0	0
T.inflata	12	0.4	0	0	0	0
J.macrescens	3	0.1	0	0	0	0
TOTAL	3099	100	21		1	5
E6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	32	1	0	0	0	0
E.Williamsoni	1088	40	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1608	59	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2728	100	0		0	0
E7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	256	10	0	0	0	0
E.Williamsoni	1080	43	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1194	47	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2530	100	0		0	0

E8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	256	13	0	0	0	0
E.Williamsoni	720	36	0	0	0	0
A.beccarii	128	6	0	0	0	0
M.fusca	880	44	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	32	2	0	0	0	0
TOTAL	2016	100	0		0	0
E9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	368	16	0	0	0	0
E.Williamsoni	984	43	72	7	3	5
A.beccarii	0	0	0	0	0	0
M.fusca	896	39	0	0	0	0
T.inflata	8	0.3	0	0	0	0
J.macrescens	32	1	0	0	0	0
TOTAL	2288	100	72		3	5
E10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	216	12	18	8	1	1.5
E.Williamsoni	1040	57	16	2	1	1.5
A.beccarii	0	0	0	0	0	0
M.fusca	560	30	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	24	1	0	0	0	0
TOTAL	1840	100	34		2	3
OW11	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	168	8.5	0	0	0	0
E.Williamsoni	1296	65	0	0	0	0
A.beccarii	64	3	0	0	0	0
M.fusca	448	23	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	8	0.4	0	0	0	0
TOTAL	1984	100	0		0	0
OW12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	1920	73	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	704	27	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2624	100	0		0	0
OW14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	312	15.5	11	4	0.4	1
E.Williamsoni	632	31.3	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1072	53.2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2016	100	11		0.4	1
OW15	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	648	21	0	0	0	0
E.Williamsoni	1608	51	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	896	28	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	3152	100	0		0	0

CM16	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	261	13	25	10	1	3
E.Williamsoni	486	24	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1245	61	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	51	2	0	0	0	0
TOTAL	2043	100	25		1	3
CM17	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	32	1	0	0	0	0
E.Williamsoni	688	19	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	2820	80	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	3540	100	0		0	0
S18	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	448	25	0	0	0	0
E.Williamsoni	1048	60	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	264	15	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1760	100	0		0	0
S19	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	512	29	0	0	0	0
E.Williamsoni	1040	58	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	240	13	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1792	100	0		0	0
S20	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	160	18	0	0	0	0
E.Williamsoni	608	69	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	112	13	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	880	100	0		0	0

F1/Spring 93	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
HP2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	10	2	0	0	0	0
E.Williamsoni	10	2	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	590	94	10	2	2	0
T.inflata	10	2	0	0	0	0
J.macrescens	10	2	0	0	0	0
TOTAL	630	100	10		2	0
HP3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
HP4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	20	10	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	180	90	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	200	100	0		0	0
E5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	160	4	20	13	0.5	1
E.Williamsoni	2420	56	60	2.5	1.4	2
A.beccarii	0	0	0	0	0	0
M.fusca	1710	40	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4290	100	80		2	3
E6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	380	11	20	5	1	1
E.Williamsoni	1610	46	20	1	1	1
A.beccarii	0	0	0	0	0	0
M.fusca	1500	43	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	3490	100	40		2	2
E7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	640	11	20	3	0.4	1
E.Williamsoni	2510	45	100	4	2	3
A.beccarii	0	0	0	0	0	0
M.fusca	2490	44	20	1	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	5640	100	140		2	4

2.2 Erme Estuary

E8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	140	5	10	7	0.4	1
E.Williamsoni	1470	55	30	2	1	2
A.beccarii	20	1	0	0	0	0
M.fusca	1060	39	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2690	100	40		1.4	3
E9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	530	11.6	0	0	0	0
E.Williamsoni	3110	68	40	1	1	1
A.beccarii	40	1	0	0	0	0
M.fusca	870	19	0	0	0	0
T.inflata	20	0.4	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4570	100	40		1	1
E10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	50	7	0	0	0	0
E.Williamsoni	320	47	10	3	1.5	3
A.beccarii	0	0	0	0	0	0
M.fusca	310	46	0	0	.0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	680	100	10		1.5	3
OW11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	220	4	20	9	0.4	0.5
E.Williamsoni	3690	71.7	30	1	0.6	1
A.beccarii	20	0.4	0	0	0	0
M.fusca	1220	23.7	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	5150	100	50		1	1.5
OW12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	160	20.5	0	0	0	0
E.Williamsoni	520	67	10	2	1	1.5
A.beccarii	0	0	0	0	0	0
M.fusca	90	11.5	0	0	0	0
T.inflata	10	1	10	100	1	0
J.macrescens	0	0	0	0	0	0
TOTAL	780	100	20		2	1.5
OW14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1170	25	20	2	0.4	0.5
E.Williamsoni	2760	58	30	1	1	0.8
A.beccarii	0	0	0	0	0	0
M.fusca	830	17	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4760	100	50		1.5	1.3
OW15	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	890	40	10	1	1	0.5
E.Williamsoni	1070	48	50	5	2	2.5
A.beccarii	20	1	0	0	0	0
M.fusca	240	11	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2220	100	60		3	3

CM16	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	110	8	20	18	2	4.4
E.Williamsoni	340	26	10	3	1	2.2
A.beccarii	0	0	0	0	0	0
M.fusca	880	66	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1330	100	30		3	7
CM17	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	410	14	10	2	0.3	0.4
E.Williamsoni	2280	78	20	1	1	0.7
A.beccarii	0	0	0	0	0	0
M.fusca	250	9	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2940	100	30		1.5	1
S18	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	910	20	10	1	0.2	0.3
E.Williamsoni	2730	60	30	1	1	0.8
A.beccarii	310	7	0	0	0	0
M.fusca	590	13	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4540	100	40		1.3	1
S19	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	320	14	0	0	0	0
E.Williamsoni	1690	74	30	2	1	1.5
A.beccarii	0	0	0	0	0	0
M.fusca	270	12	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2280	100	30		2	1.5
S20	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	750	34	0	0	0	0
E.Williamsoni	890	41	10	1	0.5	0.6
A.beccarii	0	0	0	0	0	0
M.fusca	540	25	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2180	100	10		0.5	0.6

F1/Summer 93	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						

HP2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						

HP3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						

HP4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						

E5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**64**	6	**0**	0	0	**0**
E.Williamsoni	**480**	46	**67**	14	6	**12**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**432**	42	**0**	0	0	**0**
T.inflata	**32**	3	**0**	0	0	**0**
J.macrescens	**32**	3	**0**	0	0	**0**
TOTAL	**1040**	100	**67**		6	**12**

E6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**80**	5	**0**	0	0	**0**
E.Williamsoni	**528**	35	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**880**	59	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**1488**	100	**0**		0	**0**

E7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**136**	13	**0**	0	0	**0**
E.Williamsoni	**424**	40	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**456**	44	**0**	0	0	**0**
T.inflata	**32**	3	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**1048**	100	**0**		0	**0**

E8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	256	4	0	0	0	0
E.Williamsoni	5184	81	70	1	1	1
A.beccarii	64	1	0	0	0	0
M.fusca	832	13	0	0	0	0
T.inflata	64	1	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	6400	100	70		1	1
E9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	192	38	0	0	0	0
E.Williamsoni	96	19	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	224	44	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	512	100	0		0	0
E10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	176	28	0	0	0	0
E.Williamsoni	272	44	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	112	18	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	10	0	0	0	0
TOTAL	624	100	0		0	0
OW11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	336	12	0	0	0	0
E.Williamsoni	1424	49	132	9	5	7
A.beccarii	160	5	30	19	1	2
M.fusca	608	21	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	384	13	0	0	0	0
TOTAL	2912	100	162		6	9
OW12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	944	45	64	7	3	4
E.Williamsoni	504	24	0	0	0	0
A.beccarii	128	6	0	0	0	0
M.fusca	512	25	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2088	100	64		3	4
OW14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	960	41	32	3	1	1.5
E.Williamsoni	1248	53	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	160	7	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2368	100	32		1	1.5
OW15	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	664	63	0	0	0	0
E.Williamsoni	320	31	37	12	4	3
A.beccarii	0	0	0	0	0	0
M.fusca	64	6	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1048	100	37		3	3

CM16	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	No data		No data			
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
CM17	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	No data		No data			
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
S18	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**1040**	46	**62**	6	3	**3**
E.Williamsoni	**1072**	47	**0**	0	0	**0**
A.beccarii	**96**	4	**0**	0	0	**0**
M.fusca	**64**	3	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**2272**	100	**62**		3	**3**
S19	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**736**	26	**0**	0	0	**0**
E.Williamsoni	**2048**	74	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**0**	0	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**2784**	100	**0**		0	**0**
S20	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**496**	39	**0**	0	0	**0**
E.Williamsoni	**544**	42.5	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**224**	17.5	**0**	0	0	**0**
T.inflata	**16**	1	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**1280**	100	**0**		0	**0**

F1/Autumn 93	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica						
E.Williamsoni						
A.beccarii						
M.fusca						
T.inflata						
J.macrescens						
TOTAL						
HP2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	320	83	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	17	0	0	0	0
TOTAL	384	100	0		0	0
HP3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1984	94	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	128	6	0	0	0	0
TOTAL	2112	100	0		0	0
HP4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	864	96	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	32	4	20	63	2	0
TOTAL	896		20		2	0
E5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	264	8	40	15	1	2.5
E.Williamsoni	1320	40	8	1	0	0.5
A.beccarii	0	0	0	0	0	0
M.fusca	1736	52	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	3320	100	48		1	3
E6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	192	10	0	0	0	0
E.Williamsoni	976	52	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	704	37	0	0	0	0
T.inflata	8	0	0	0	0	0
J.macrescens	8	0	0	0	0	0
TOTAL	1888	100	0		0	0
E7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	208	19	0	0	0	0
E.Williamsoni	528	49	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	336	31	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1072	100	0		0	0

E8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	416	28	0	0	0	0
E.Williamsoni	752	51	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	288	19	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	32	2	0	0	0	0
TOTAL	1488	100	0		0	0
E9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	352	23	0	0	0	0
E.Williamsoni	944	62	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	136	9	0	0	0	0
T.inflata	64	4	0	0	0	0
J.macrescens	32	2	0	0	0	0
TOTAL	1528	100	0		0	0
E10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	96	25.5	0	0	0	0
E.Williamsoni	160	43	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	48	13	0	0	0	0
T.inflata	8	2	0	0	0	0
J.macrescens	64	17	0	0	0	0
TOTAL	376	100	0		0	0
OW11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	40	19	8	20	4	1
E.Williamsoni	176	81	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	216	100	8		1	1
OW12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	64	4	0	0	0	0
E.Williamsoni	1408	88	0	0	0	0
A.beccarii	64	4	0	0	0	0
M.fusca	64	4	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1600	100	0		0	0
OW14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1008	35	30	3	1	1.3
E.Williamsoni	1264	44	57	5	2	2.5
A.beccarii	0	0	0	0	0	0
M.fusca	608	21	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2880		87		3	4
OW15	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	128	9	16	12.5	1	1
E.Williamsoni	1136	80	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	160	11	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1424	100	16		1	1

CM16	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	160	31	0	0	0	0
E.Williamsoni	152	29	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	192	37	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	16	3	0	0	0	0
TOTAL	520	100	0		0	0
CM17	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	168	35	0	0	0	0
E.Williamsoni	88	18	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	224	47	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	480	100	0		0	0
S18	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	64	7	0	0	0	0
E.Williamsoni	808	92	24	3	3	3
A.beccarii	0	0	0	0	0	0
M.fusca	8	1	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	880	100	24		3	3
S19	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	152	13	0	0	0	0
E.Williamsoni	824	71	16	2	1	1.6
A.beccarii	0	0	0	0	0	0
M.fusca	192	16	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1168	100	16		1	1.6
S20	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	288	72	16	6	4	4
E.Williamsoni	96	24	32	33	8	8
A.beccarii	0	0	0	0	0	0
M.fusca	16	4	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	400	100	48		12	12

StW1/Spring 94	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	42	54	2	5	3	4
E.Williamsoni	2	3	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	33	43	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	77	100	2			4
StW2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	74	29.3	0	0	0	0
E.Williamsoni	26	10.5	0	0	0	0
A.beccarii	4	1.6	0	0	0	0
M.fusca	146	58.4	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	250	100	0		0	0
LPO3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	50	100	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	50	100	0		0	0
RC4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	4	7	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	57	93	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	61	100	0		0	0
CH5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1346	91	24	2	2	2
E.Williamsoni	92	6	2	2	0.14	0.14
A.beccarii	0	0	0	0	0	0
M.fusca	40	3	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1478	100	26		2	2
CH6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1936	99.6	9	0.5	0.5	0.5
E.Williamsoni	8	0.4	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1944	100	9		0.5	0.5
PM7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	62	57	0	0	0	0
E.Williamsoni	39	36	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	8	7	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	109	100	0		0	0

MP9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	466	95	0	0	0	0
E.Williamsoni	25	5	7	28	1	1
A.beccarii	1	0.2	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	492	100	7		1	1
MP10	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	2004	82.5	24	1	1	1
E.Williamsoni	376	16	8	2	0.33	0.3
A.beccarii	28	1.2	0	0	0	0
M.fusca	16	0.7	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2424	100	32		1.3	1
PPH11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	2024	97	20	1	1	1
E.Williamsoni	18	1.1	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	34	1.5	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2076	100	20		1	1
G12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	428	69	20	5	3	4
E.Williamsoni	56	9.5	0	0	0	0
A.beccarii	64	10.5	4	6	1	1
M.fusca	56	9	0	0	0	0
T.inflata	12	1.7	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	616	100	24		4	5
G13	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	948	89.5	11	1	1	1
E.Williamsoni	96	9	4	4	0.4	0.4
A.beccarii	16	1.5	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1060	100	15		1.4	1
G14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	2756	97	12	0.4	0.4	0.4
E.Williamsoni	80	2.8	16	20	0.6	0.6
A.beccarii	12	0.4	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2848	100	28		1	1

StW1/Summer 94	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	363	79.2	2	0.6	0.4	0.5
E.Williamsoni	8	2	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	88	19	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	459	100	2		0.4	0.5
StW2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	394	93	6	2	1	1.5
E.Williamsoni	8	2	4	50	1	1
A.beccarii	0	0	0	0	0	0
M.fusca	15	3.7	0	0	0	0
T.inflata	2	0.5	0	0	0	0
J.macrescens	4	1	0	0	0	0
TOTAL	423	100	10		2	2.5
LPO3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	123	88	1	1	1	0.8
E.Williamsoni	10	7	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	7	4.7	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	140	100	1		1	1
RC4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	294	64	6	2	1	2
E.Williamsoni	12	3	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	148	33	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	454	100	6		1	2
CH5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1392	97	20	1	1	1
E.Williamsoni	24	2	0	0	0	0
A.beccarii	8	0.6	0	0	0	0
M.fusca	8	0.6	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1432	100	20		1	1
CH6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1084	90	16	1.5	1.3	1
E.Williamsoni	82	7	0	0	0	0
A.beccarii	18	1.5	0	0	0	0
M.fusca	16	1.3	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1200	100	16		1.3	1
PM7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	314	90	6	2	2	2
E.Williamsoni	28	8	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	9	2.3	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	351	100	6		2	2

MP9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1560	93	0	0	0	0
E.Williamsoni	112	6.5	0	0	0	0
A.beccarii	12	0.75	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1684	100	0		0	0
MP10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1392	80	36	3	2	2
E.Williamsoni	264	14.5	0	0	0	0
A.beccarii	56	3.5	8	14	0.5	0.5
M.fusca	32	2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1744	100	44		2.5	2.5
PPH11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	443	60	6	1	1	1
E.Williamsoni	296	39	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	8	1	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	747	100	6		1	1
G12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1744	64	16	1	1	1
E.Williamsoni	828	30	0	0	0	0
A.beccarii	128	5	0	0	0	0
M.fusca	32	1	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2732	100	16		1	1
G13	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	98	75	0	0	0	0
E.Williamsoni	32	25	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	130	100	0		0	0
G14	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	476	65	16	3	2	2
E.Williamsoni	236	32.6	0	0	0	0
A.beccarii	8	1	0	0	0	0
M.fusca	8	1	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	728	100	16		2	2

StW1/Autumn 94	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	236	40	12	5	2	3
E.Williamsoni	113	19.2	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	240	41	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	589	100	12		2	3
StW2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	244	15	0	0	0	0
E.Williamsoni	1278	79	32	2.5	2	2
A.beccarii	32	2	0	0	0	0
M.fusca	66	4	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1620	100	32		2	2
LPO3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	22	80	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	3	20	0	0	0	0
TOTAL	25	100	0		0	0
RC4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	66	19.6	0	0	0	0
E.Williamsoni	104	31	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	164	49.2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	334	100	0		0	0
CH5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	120	24	0	0	0	0
E.Williamsoni	378	76	26	7	5	5
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	498	100	26		5	5
CH6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	96	24	0	0	0	0
E.Williamsoni	296	73	0	0	0	0
A.beccarii	12	3	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	404	100	0		0	0
PM7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	196	37	0	0	0	0
E.Williamsoni	332	63	20	6	4	4
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	528	100	20		4	4

MP9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	120	50	0	0	0	0
E.Williamsoni	116	48	0	0	0	0
A.beccarii	4	2	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	240	100	0			0
MP10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	280	44	0	0	0	0
E.Williamsoni	306	47	8	3	1	1
A.beccarii	50	8.5	0	0	0	0
M.fusca	2	0.5	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	638	100	8		1	1
PPH11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	28	47	0	0	0	0
E.Williamsoni	24	40	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	8	13	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	60	100	0		0	0
G12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	380	41	0	0	0	0
E.Williamsoni	496	54	20	4	2.2	2.2
A.beccarii	38	4.7	2	5	0.2	0.2
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	2	0.2	0	0	0	0
TOTAL	916	100	22		2.4	2
G13	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	836	37.5	48	6	2	2
E.Williamsoni	1160	50.9	8	0.7	0.4	0.4
A.beccarii	224	10.4	4	2	0.2	0.2
M.fusca	32	1.5	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2252	100	60		3	3
G14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	208	41	0	0	0	0
E.Williamsoni	292	57	8	3	2	2
A.beccarii	0	0	0	0	0	0
M.fusca	8	2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	508	100	8		2	2

2.3 Fowey Estuary

StW1/Winter 95	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	**40**	3	**0**	0	0	**0**
E.Williamsoni	**34**	3	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**1110**	94	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**1184**	100	**0**		0	**0**
StW2	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**%Cal**
H.germanica	**46**	19	**0**	0	0	**0**
E.Williamsoni	**172**	71	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**24**	10	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**242**	100	**0**		0	**0**
LPO3	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**%Cal**
H.germanica	**0**	0	**0**	0	0	**0**
E.Williamsoni	**0**	0	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**10**	100	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**10**	100	**0**		0	**0**
RC4	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**0**
H.germanica	**0**	0	**0**	0	0	**0**
E.Williamsoni	**0**	0	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**240**	100	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**240**	100	**0**		0	**0**
CH5	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**%Cal**
H.germanica	**202**	55	**0**	0	0	**0**
E.Williamsoni	**148**	41	**12**	8	3	**3**
A.beccarii	**8**	2	**0**	0	0	**0**
M.fusca	**8**	2	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**366**	100	**12**		3	**3**
CH6	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**%Cal**
H.germanica	**8**	20	**0**	0	0	**0**
E.Williamsoni	**22**	55	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**10**	25	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**40**	100	**0**		0	**0**
PM7	**SC/T**	**%T**	**DSC/T**	**% Sp**	**%T**	**%Cal**
H.germanica	**418**	58	**0**	0	0	**0**
E.Williamsoni	**226**	31.5	**0**	0	0	**0**
A.beccarii	**0**	0	**0**	0	0	**0**
M.fusca	**74**	10.4	**0**	0	0	**0**
T.inflata	**0**	0	**0**	0	0	**0**
J.macrescens	**0**	0	**0**	0	0	**0**
TOTAL	**718**	100	**0**		0	**0**

MP9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	70	28	0	0	0	0
E.Williamsoni	156	62	0	0	0	0
A.beccarii	22	8.4	0	0	0	0
M.fusca	4	2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	252	100	0		0	0
MP10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	12	11.5	0	0	0	0
E.Williamsoni	76	73	0	0	0	0
A.beccarii	12	11.5	0	0	0	0
M.fusca	4	4	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	104	100	0		0	0
PPH11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	40	71	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	16	29	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	56	100	0		0	0
G12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	440	40	16	4	1	0
E.Williamsoni	160	15	0	0	0	0
A.beccarii	180	16.4	0	0	0	0
M.fusca	320	29	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1100	100	16		1	0
G13	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	132	32	0	0	0	0
E.Williamsoni	152	36.5	0	0	0	0
A.beccarii	120	29.5	8	7	2	2
M.fusca	8	2	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	412	100	8		2	2
G14	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	26	100	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	26	100	0		0	0

A1/Summer 95	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	128	8	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1366	88	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	4	0	0	0	0
TOTAL	1556	100	0		0	0
A2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	164	12	64	39	5	19.5
E.Williamsoni	148	11	16	11	1	5
A.beccarii	16	1	16	100	1	5
M.fusca	980	75	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1308	100	96			29.5
A3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1704	21	168	10	2	3
E.Williamsoni	2288	28	160	7	2	3
A.beccarii	1864	22	32	2	0.4	0
M.fusca	2264	28	32	1	0.4	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	1	0	0	0	0
TOTAL	8184	100	392		5	6
A4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	920	29	64	7	2	3
E.Williamsoni	744	23	0	0	0	0
A.beccarii	200	6	0	0	0	0
M.fusca	1160	36	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	192	6	0	0	0	0
TOTAL	3216	100	64		2	3
A5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	620	18	0	0	0	0
E.Williamsoni	396	23	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	992	57	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	32	2	0	0	0	0
TOTAL	1740	100	0		0	0
A6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1176	12	0	0	0	0
E.Williamsoni	7232	76	16	0.22	0.17	0.18
A.beccarii	144	1	0	0	0	0
M.fusca	960	10	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	72	1	0	0	0	0
TOTAL	9584	100	16		0.17	0.18
A7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1464	30	128	9	3	4
E.Williamsoni	1928	41	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1224	25	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	192	4	0	0	0	0
TOTAL	4808	100	128		3	4
A8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1424	24	8	0.56	0.13	0.17
E.Williamsoni	3160	53	0	0	0	0
A.beccarii	128	2	0	0	0	0
M.fusca	1216	21	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	5928	100	8		0.13	0.17

A9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	4	6	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	68	95	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	72	100	0		0	0
A10	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	264	15	0	0	0	0
E.Williamsoni	680	38	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	832	47	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1776	100	0		0	0
A11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	3786	23	0	0	0	0
E.Williamsoni	6136	38	0	0	0	0
A.beccarii	1730	10	0	0	0	0
M.fusca	4546	27	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	256	2	0	0	0	0
TOTAL	16454	100	0		0	0
A12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	328	21	0	0	0	0
E.Williamsoni	1008	64	0	0	0	0
A.beccarii	128	8	0	0	0	0
M.fusca	96	6	0	0	0	0
T.inflata	8	1	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1568	100	0		0	0

A1/Autumn 95	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	64	7	16	25	2	6.5
E.Williamsoni	176	18	8	5	1	3
A.beccarii	8	1	0	0	0	0
M.fusca	712	74	16	2	2	6.5
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	960	100	40		5	16
A2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	16	4	0	0	0	0
E.Williamsoni	152	37	0	0	0	0
A.beccarii	8	2	0	0	0	0
M.fusca	232	57	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	408	100	0		0	0
A3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	432	11	0	0	0	0
E.Williamsoni	560	14	0	0	0	0
A.beccarii	2112	53	0	0	0	0
M.fusca	896	22	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4000	100	0		0	0
A4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	560	16	0	0	0	0
E.Williamsoni	1168	34	0	0	0	0
A.beccarii	1024	30	64	6	2	2
M.fusca	640	19	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	3392	100	64		2	2
A5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	128	5	0	0	0	0
E.Williamsoni	1732	73	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	512	22	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2372	100	0		0	0
A6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	128	12	32	25	3	6
E.Williamsoni	128	12	0	0	0	0
A.beccarii	320	30	0	0	0	0
M.fusca	384	37	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	96	9	0	0	0	0
TOTAL	1056	100	32		3	6
A7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	720	8	0	0	0	0
E.Williamsoni	6968	73	16	0.23	0.17	0.17
A.beccarii	1776	19	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	128	1	0	0	0	0
TOTAL	9592	100	16		0.17	0.17
A8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	280	34	16	6	2	6
A.beccarii	0	0	0	0	0	0
M.fusca	512	62	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	32	4	0	0	0	0
TOTAL	824	100	16			6

A9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	116	11	16	14	1	1.7
E.Williamsoni	832	74	32	4	3	3
A.beccarii	0	0	0	0	0	0
M.fusca	180	16	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1128	100	48		4	5
A10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	80	2	8	10	0.2	0.2
E.Williamsoni	4200	85.4	8	0.2	0.2	0.2
A.beccarii	64	1	0	0	0	0
M.fusca	512	11	0	0	0	0
T.inflata	8	0	0	0	0	0
J.macrescens	64	1	0	0	0	0
TOTAL	4928	100	16		0.4	0.4
A11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	908	12	0	0	0	0
E.Williamsoni	3016	38	32	1	0	0.6
A.beccarii	1088	14	128	12	2	3
M.fusca	2592	33	128	5	2	3
T.inflata	0	0	0	0	0	0
J.macrescens	292	4	0	0	0	0
TOTAL	7896	100	288		4	7
A12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	48	4	0	0	0	0
E.Williamsoni	1052	93	12	1	1	1
A.beccarii	0	0	0	0	0	0
M.fusca	32	3	32	100	3	0
T.inflata	4	0.4	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1136	100	44		4	1

A1/Winter 96	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1008	100	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1008	100	0		0	0
A2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	96	13	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	624	87	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	720	100	0		0	0
A3	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	160	5	0	0	0	0
E.Williamsoni	1784	62	16	1	0.6	0.7
A.beccarii	256	9	0	0	0	0
M.fusca	672	24	32	5	1	1.5
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2872	100	48		1.7	2
A4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	28	5	0	0	0	0
E.Williamsoni	288	46	32	11	5	8
A.beccarii	64	10	0	0	0	0
M.fusca	256	40	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	636	100	32		5	8
A5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	16	5	0	0	0	0
E.Williamsoni	193	60	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	112	35	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	321	100	0		0	0
A6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	64	3	0	0	0	0
E.Williamsoni	576	25	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1664	72	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2304	100	0		0	0
A7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1328	16	0	0	0	0
E.Williamsoni	4976	58	0	0	0	0
A.beccarii	256	3	0	0	0	0
M.fusca	1664	19	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	384	5	0	0	0	0
TOTAL	8608	100	0		0	0
A8	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	368	17	32	9	1	2
E.Williamsoni	928	40	64	7	3	5
A.beccarii	32	1	0	0	0	0
M.fusca	992	43	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2320	100	96		4	7

A9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	34	1	0	0	0	0
E.Williamsoni	736	33	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1474	65	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	16	1	0	0	0	0
TOTAL	2260	100	0		0	0
A10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	72	1	0	0	0	0
E.Williamsoni	3936	86	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	576	13	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4584	100	0		0	0
A11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	1122	12	0	0	0	0
E.Williamsoni	4516	46	0	0	0	0
A.beccarii	384	4	0	0	0	0
M.fusca	3648	38	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	1	0	0	0	0
TOTAL	9734	100	0		0	0
A12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	72	2	0	0	0	0
E.Williamsoni	3504	83	136	4	3	4
A.beccarii	0	0	0	0	0	0
M.fusca	0	0	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	640	15	0	0	0	0
TOTAL	4216	100	136		3	4

A1/Spring 96	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	56	25	8	14	4	14
A.beccarii	0	0	0	0	0	0
M.fusca	168	75	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	224	100	8		4	14
A2	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	16	3	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	560	97	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	576	100	0		0	0
A3	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	320	9	12	4	0.3	0.5
E.Williamsoni	1644	39	0	0	0	0
A.beccarii	576	14	0	0	0	0
M.fusca	1600	38	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	4140	100	12		0.3	0.5
A4	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	24	1	0	0	0	0
E.Williamsoni	888	38	0	0	0	0
A.beccarii	272	12	0	0	0	0
M.fusca	1176	49	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2360	100	0		0	0
A5	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	32	33	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	64	67	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	96	100	0		0	0
A6	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	112	6	0	0	0	0
E.Williamsoni	408	21	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	1464	73	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1984	100	0		0	0
A7	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	448	20	0	0	0	0
E.Williamsoni	736	33	0	0	0	0
A.beccarii	192	9	0	0	0	0
M.fusca	864	38	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	2240	100	0		0	0
A8	SC/T	%T	DSC/T	% Sp	%T	0
H.germanica	144	11	0	0	0	0
E.Williamsoni	736	55	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	448	34	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	1328	100	0		0	0

A9	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	0	0	0	0	0	0
E.Williamsoni	0	0	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	544	100	16	3	3	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	544	100	16		3	0
A10	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	32	11	0	0	0	0
E.Williamsoni	232	78	32	14	11	12
A.beccarii	0	0	0	0	0	0
M.fusca	32	11	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	296	100	32		11	12
A11	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	206	6	0	0	0	0
E.Williamsoni	300	8	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	3136	85	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	64	2	0	0	0	0
TOTAL	3706	100	0		0	0
A12	SC/T	%T	DSC/T	% Sp	%T	%Cal
H.germanica	32	5	0	0	0	0
E.Williamsoni	196	30	0	0	0	0
A.beccarii	0	0	0	0	0	0
M.fusca	432	65	0	0	0	0
T.inflata	0	0	0	0	0	0
J.macrescens	0	0	0	0	0	0
TOTAL	660	100	0		0	0

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Note of poster display at the Annual Conference of the Ussher Society, January 1993

RECENT BENTHIC FORAMINIFERIDA AS INDICATORS OF POLLUTION IN RESTRONGUET CREEK, CORNWALL

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Proceedings of the Ussher Society

INTRODUCTION

'ollowing a discharge of acidic mine water highly contaminated vith heavy metals from Wheal Jane tin mine (13.1.92), a ›reliminary investigation has been made to determine the esponse of foraminifera when exposed to polluted water. The nitial results of the research are given in this paper.

'REVIOUS RESEARCH

'here is no known database of foraminiferal species distribution ı Restronguet Creek, nor has any previous investigation of the sefulness of benthic foraminiferans as pollution indicators een carried out at this location. The potential use of benthic ›raminiferans as indicators of pollution in other estuaries has, owever, been examined by a number of workers.

Recent work carried out by Sharifi *et al.* (1991) on outhampton Water found abnormal foraminiferal test growth esulted from exposure to increased levels of Cu and Zn. Alve 1991) and Ellison *et al.* (1986) concluded that a low abundance f living foraminifera and an increase in diversity away from the ›urce of contamination is indicative of metal contamination.

ISTORICAL PERSPECTIVES

estronguet Creek provides a unique site for investigation ecause of the additional complication of the long history of eavy metal contamination.

Within the catchment areas of the rivers Kennal and ırnon which feed into Restronguet Creek (Figure 1), etalliferous mining has taken place for several centuries arton, 1967) and prior to the recent discharge from Wheal ne, both rivers, and in particular the Carnon, have received scharged mine waters. Prior to 1854, when the precipitation chnique was initiated to remove copper and other metals, treated water was discharged (Hamilton Jenkin, 1963).

Of the mines which drained into the Carnon and Kennal, eal Jane was for, several years, the last working mine. The a had, therefore, experienced a period of quiescence with pect to mine water discharge, with no major discharges noted mpson, 1992, personal communication). The abandoned mines , however, flooded and remain sources of contaminated chate. There also remains the unanswered question of the ount of contamination caused by the natural processes of mical and physical weathering of metalliferous veins.

The most recent discharge occurred after the mine ceased rking in February 1991, as up until this time the mine had n kept dry. After closure Wheal Jane was allowed to flood. lowing prolonged heavy rain and strong winds the existing tment measures failed and 320 million litres of untreated er discharged into the Carnon over a period of 60 hours rnon Consolidated, 1992). The concentrations of heavy als in the sediment detected after this discharge are phically illustrated by Figure 2.

TER CONDITIONS

hwater flow is often vigorous with respect to the Kennal Carnon and tidal influence is restricted to below Devoran bridge [SW 790 394]. At low water extensive areas of flats are exposed, with small isolated areas of saltmarsh. ities vary from 5ppt at Carclew in the winter to a maximum of 31ppt in the summer. Further down the creek at Harcourt, values rise to 30ppt in the winter and 33ppt in the summer. Carrick Roads, the estuary of the Fal (Figure 1), has salinities of a normal marine environment; 34ppt.

METHODS

With increased depth the abundance of living foraminiferans decreases (Murray, 1991). The cores Boltovoskoy (1966) took from Deseado Creek, Chile showed diversity and the number of specimens per cc. of sediment decreased with increased depth. Boltovoskoy (1966) did, however, find living foraminiferans at a 16 cm depth but suggested that the substrate type and the depth of the oxidised zone would be controlling parameters. Similar work carried out by other researchers also found living foraminiferans existed at these greater depths (Buzas, 1969, 1974; Steinack and Bergstein, 1979).

This preliminary investigation is limited to foraminiferal response to a recent contaminated discharge and the ratio of living to dead individuals is an important consideration. Sampling, therefore, was restricted to a 1 cm depth as sampling deeper would distort the live/dead ratio and would be unrepresentative.

The sample sites selected follow lateral transects along both sides of the creek within the intertidal sections (see Figure 1). Following standard sampling techniques a 10 cm diameter ring was inserted into the sediment to a depth of 1 cm and the enclosed sediment removed by a modified dish to plastic jars containing buffered formalin. Vigorous shaking distributed the preservative.

The samples were processed in the laboratory by wet sieving on a 63 micron sieve. The >63 micron residue was transferred to a bowl and immersed in Rose Bengal (Walton, 1952) for 45 minutes to stain the protoplasm within the tests of the foraminiferans alive at the time of sampling or only recently dead. Further wet sieving removed excess stain and the residue was dried overnight at 60°C. Each dried sample was sieved through a sieve stack and the retained fractions weighed. The 250 micron and 125 micron fractions were randomly picked and a minimum 301 specimens mounted onto a grid slide. The data have been reduced to percentages for relative abundance of living and abnormal test growth. The distinction between normal and abnormal is made by reference to the type species (see Plate 1). Those specimens considered abnormal show additional chamber growth whereby one chamber is superimposed upon another, enlarged final or penultimate chambers, protruding chambers, multiple distorted chambers, twinned tests and uneven chamber or suture shape.

RESULTS

The highest percentage occurrence of living specimens was found at Tallack's Creek and this is co-incidental with a high percentage occurrence of abnormal test growth.

Sample TC3 (Figure 1) gave the highest values of stained tests (37%). The number of tests showing abnormal growth (see above) is similarly high (14%), of which over half were living (8%). As Figure 3 shows, a trend is evident and a horizontal gradient is defined, whereby the number of deformed and undeformed living both decrease away from

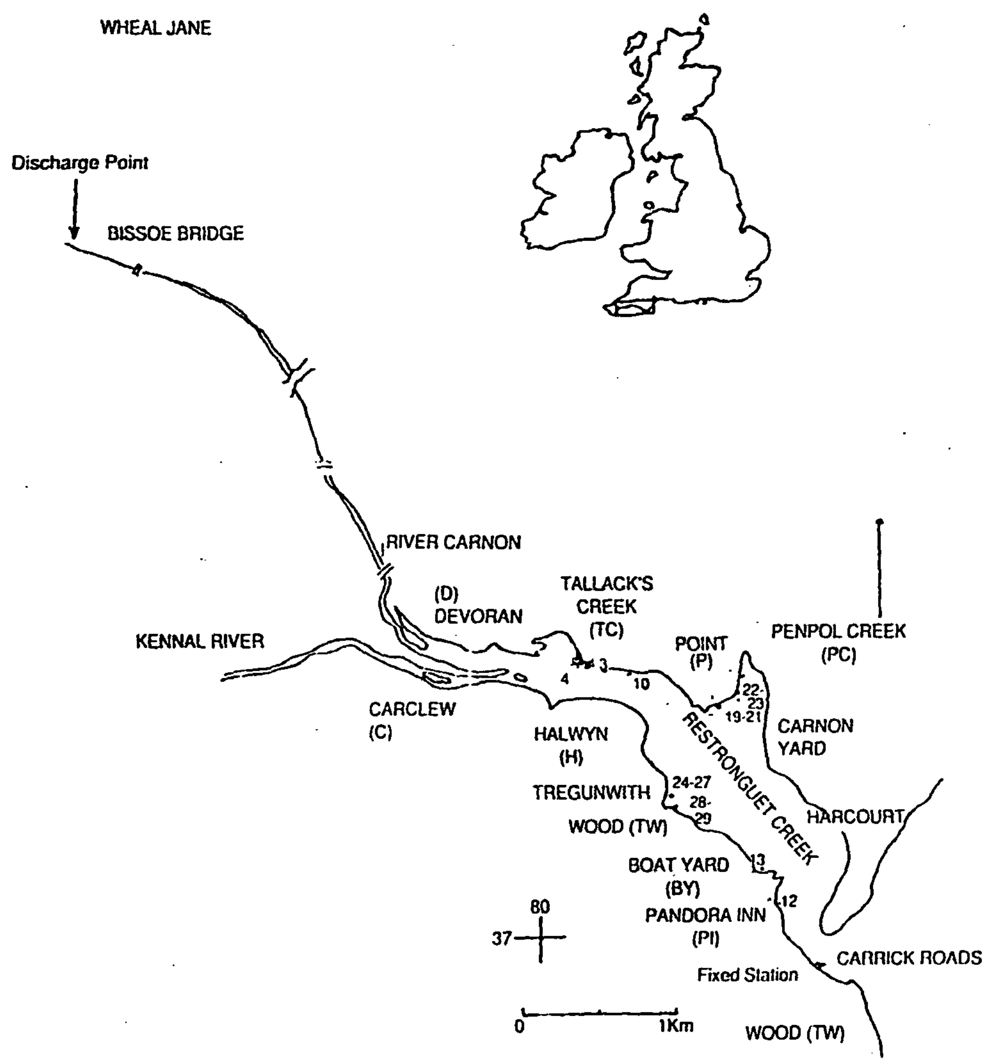
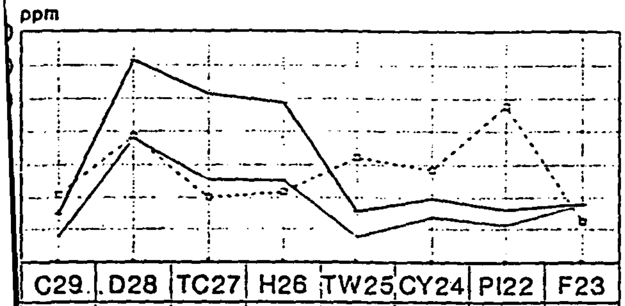


Figure 1: Locality map showing sample stations, discharge point and spatial relationship to Wheal Jane tin mine. Abbreviations of the stations are shown, eg. TW represents Tregunwith Wood.

scharge point.

regunwith Wood has the lowest percentage abundance ing (3%-8%) and deformed living specimens (<2%). e TW24 is the exception with 19% living and 2% living ned (Figure 4). A direct correlative trend is again it between live deformed and undeformed, but the ance of living increases at Pandora Inn, furthest away he point discharge.

e correlation between living deformed and undeformed niferans is positive, but some of the points scatter about



C29	D28	TC27	H26	TW25	CY24	PI22	F23
383	1891	1270	1261	382	689	569	887
742	3078	2573	2439	786	984	808	898
1.5	4	2.5	3	1	2	0.5	1.5
1039	1922	997	1085	1607	1418	2387	616

sample stations

Heavy metal contamination of sediments, Restronguet Creek. plied by the NRA (13.5.92).

the line as shown by Figures 5a. and 5b. The correlation is not, therefore, strong.

Species dominance

The species *H. germanica* dominates both the live and dead assemblages, accounting for a maximum total of 89% of sample P20 of which 13% were living. The maximum abundance of living *Haynesina germanica* was found at location TC3, accounting for 95% of the living total of 37%. The two species *E. williamsoni* and *A. beccarii* show low abundance and do not exceed 30% and 6% respectively of the total species distribution. The abundance of living is similarly low (see Figures 6a and 6b).

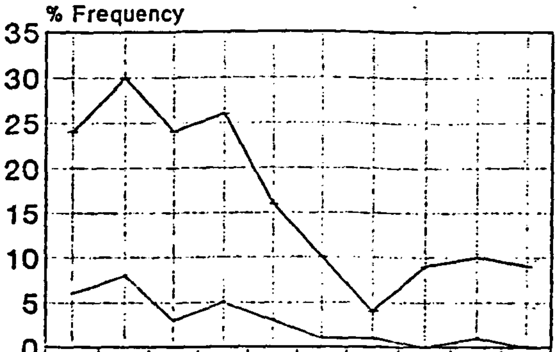
Population density

Population density (living and dead) is highest on the south side of the creek. Tregunwith Wood and the Boat Yard have values c.3000 individuals per 10 cm^2. The tests at Tregunwith Wood are in pristine condition. Few specimens show abrasion or other features indicative of transportation and/or low pH conditions. The condition of the tests from the Boat Yard show some of these features. The total population density decreases downstream to less than 800 individuals per 10 cm^2 at Pandora Inn.

On the north side of the creek at Tallack's Creek there is a paucity of specimens, with 127 per 10 cm^2 (sample TC1). Density increases away from the discharge point with an average value of 560 individuals per 10 cm^2 at sample location Point.

Diversity

There are 3 indigenous species forming the living assemblage and the Alpha Index is less than 1 (Fisher *et al.*, 1943). The three species belong to the Suborder Rotaliina. In addition to



	TC4	TC3	TC2	TC1	TC10	P20	P19	P21	PC23	PC22
ormed % —	6	8	3	5	3	1	1	0	1	0
eformed % —+—	24	30	24	26	16	10	4	9	10	9

Sample Stations

re 3: North side of creek showing the dual relationship between ng deformed and undeformed.

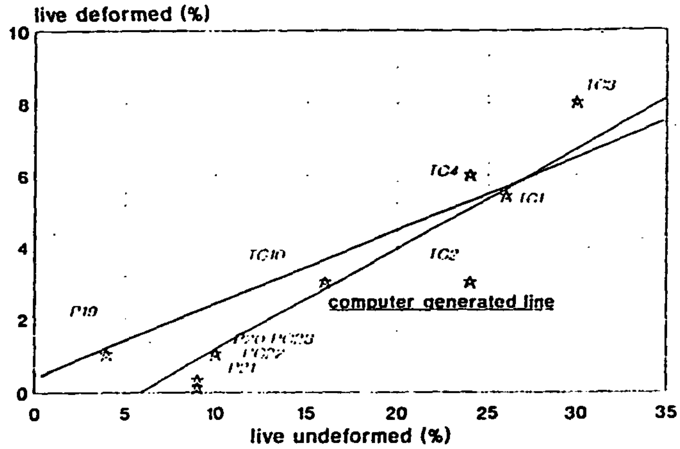
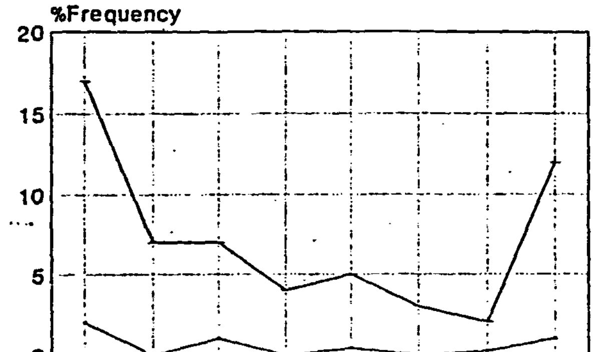


Figure 5a: North side – trend diagram of living undeformed vs deformed.



	TW24	TW25	TW26	TW27	TW28	TW29	RY13	P112
ned % —	2	0	1	0	0.4	0	0.2	1
ormed % —+—	17	7	7	4	5	3	2	12

Sample Stations

e 4: South side of Restronguet Creek.

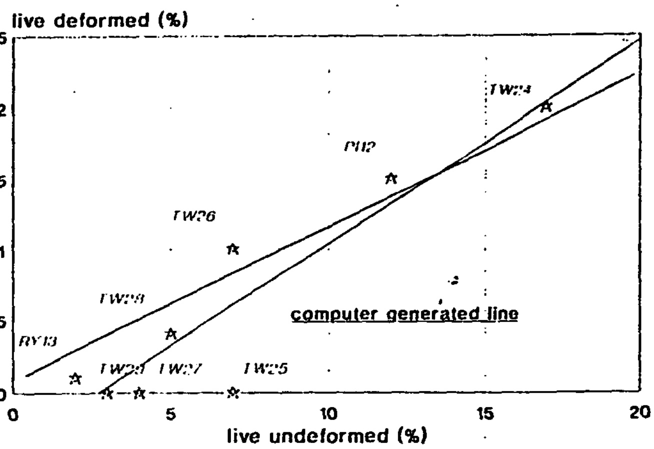


Figure 5b: South side.

ndigenous species there are a few randomly distributed es, for example, *Quinqueloculina dimidiata* Terquem and *mmina macrescens* (Brady). These were restricted to the assemblage and diversity increases slightly as a equence to a maximum of 5 species. The random and verished distribution of these minor species leads to the usion that they are an allocthonous influence from adjacent onments and/or reworked from depth.

USSION

ata derived from this preliminary investigation shows a al trend which may be assigned to a pollution control. 'allack's Creek shows a positive correlation between living ned/undeformed and the highest percentage abundance of s here, nearest to the discharge point. This is contrary to the s of Alve (1991) and Ellison *et al.* (1986), which concluded low abundance of living foraminiferans proximal to the is indicative of a pollution control. An increase in live niferan abundance proximal to the source may suggest that nmunity there is more specialised and able to cope with evels of heavy metals. The decrease in the relative nce of living deformed foraminiferans on both sides of the away from the discharge point does fit the Sharifi *et al.* model, whereby fewer deformed specimens were tered when there was no spatial relationship with a source. e majority of samples taken from Tregunwith Wood have ng abundance and deformed specimens, but high total ion density. There is a small increase in the number of oraminiferans at Pandora Inn and this may indicate an to cope with heavy metal pollution. The dilute and l effects of the relatively unpolluted river Kennal may be g the results at Tregunwith Wood, but this needs to be ated further.

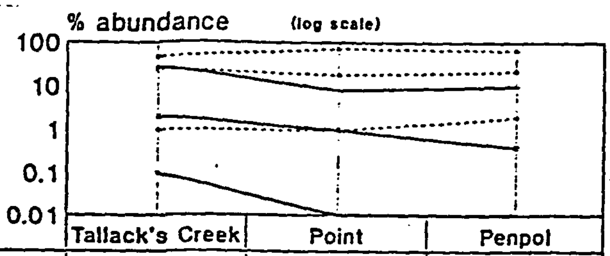
Low diversity is generally accepted as normal within an estuarine environment because of the variable conditions (Murray, 1991). The absence of the euryhaline agglutinated species, however, poses an anomaly. Living agglutinated taxa are present in the Erme estuary samples taken in 1991. At most locations the species *Miliammina fusca* (Brady) was found to be the dominant species. Research by Hart and Thompson, 1974; Murray, 1973, 1991; Boltovoskoy, 1976 and Steinack *et al.* 1979, for example, has found agglutinated species to be typical of an estuarine assemblage. The reasons for the apparent absence of the euryhaline agglutinated species is uncertain. If the variables salinity and temperature were controlling factors (Lidz, 1965), then the three indigenous calcareous euryhaline species would also be affected as they share similar tolerance thresholds (Greiner, 1969). Absence due to complete dissolution within the sometimes acidic water conditions is also unlikely as this implies selective dissolution and low pH would be more effective upon calcereous tests than agglutinated forms (Jonasson and Patterson, 1992; Murray, 1973).

The data suggest that the three species present can tolerate high concentrations of heavy metals, but other euryhaline species have lower tolerance thresholds.

FUTURE WORK

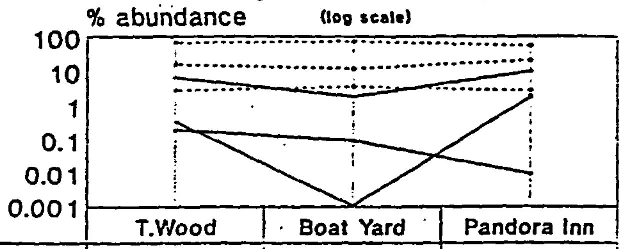
Sampling of Restronguet Creek and the control estuary, the Erme will continue at seasonal intervals. Absolute and relative abundance of deformed and undeformed living will be determined and correlated with the concentrations of heavy metals within the sediment. The tests will be analyzed by micro-probe (Jeol 6100) to detect the levels of heavy metal accumulation and this data correlated with spatial relationships to the discharge point.

Other influences and likely causes of pollution which may



		Tallack's Creek	Point	Penpol
. live	——	27	8	10
. dead	......	46	71	67
'. live	——	2	1	0.4
. dead	......	24	18	22
live	——	0.1	0	0
dead	......	1	1	2

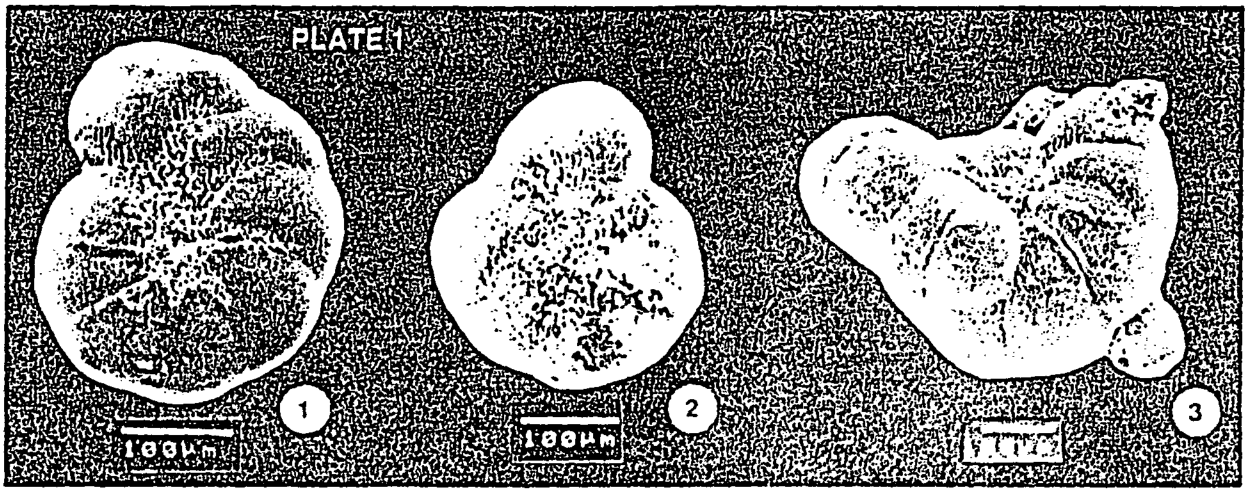
Sample stations



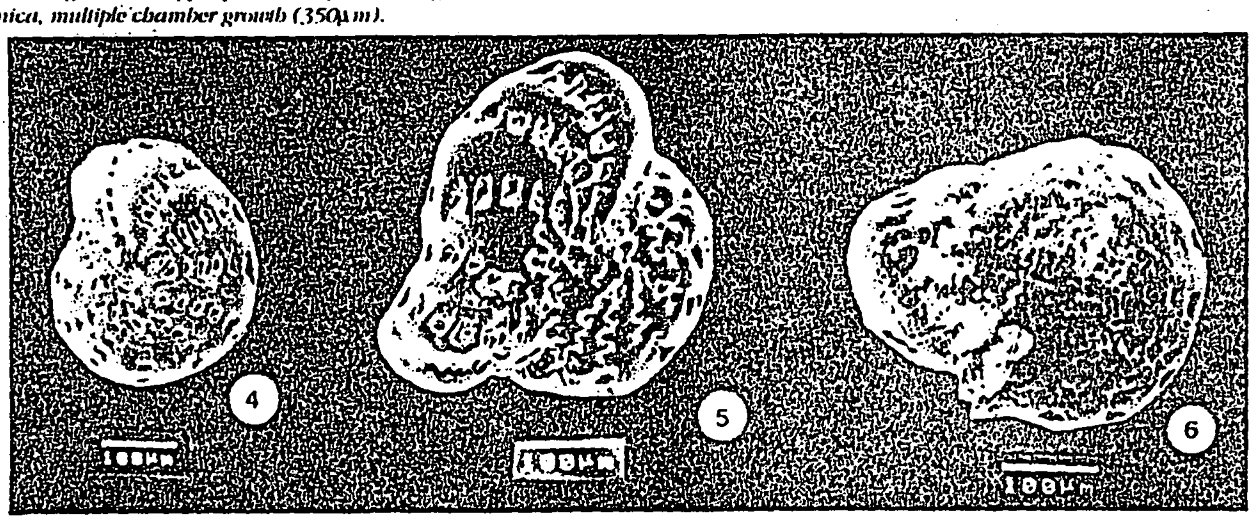
		T.Wood	Boat Yard	Pandora Inn
H.g. live	——	7	2	11
H.g. dead	......	72	81	61
E.w. live	——	0.3	0	2
E.w. dead	......	17	13	23
A.b. live	——	0.2	0.1	0.01
A.b. dead	......	3	4	3

Sample stations

gure 6: % distribution of each species and associated abundance of living specimens found on the north side (a) and south side (b) of the creek.



aynesina germanica type species (300µm). 2. H. germanica, abnormal chamber growth. Last chamber is enlarged and protruding (250µm). 3. H. manica, multiple chamber growth (350µm).



hidium williamsoni type species (300µm). 5. E.williamsoni, protruding chambers (300µm). 6. E.williamsoni, twin (325µm).

l foraminiferal distribution (absence of agglutinated taxa) st form will also be investigated.

ores will be taken and dated to determine past niferal response to heavy metal pollutions with respect to mal test growth and test accumulation of metals. The ntrations of heavy metals within the sediment will also be ined.

e future proposals for the treatment of mine tailings ater should ensure that contaminated water is not rged into the Carnon again. Future sampling for benthic niferida will provide a useful monitoring technique of oposed treatment at Wheal Jane and the present h will provide comparative data.

Acknowledgements

I am grateful to Professor Hart for the opportunity to carry out this research and his assistance in the completion of this paper. The limited financial support for field work from a PCFC research grant is much appreciated as it has enabled me to continue my research. The assistance given by other members of the department is also acknowledged, as are the data supplied by The National Rivers Authority. I am also grateful for the beneficial discussions and assistance given by Dr. C. Williams. I am very thankful for the support of my family. I acknowledge the assistance given by the referee in the completion of this paper.

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he Editor would like to apologise for the omission of the following abstract from the beginning of this article.

ollowing a recent discharge of acidic mine water contaminated with heavy metals, sediment samples were taken from estronguet Creek for a preliminary analysis of benthic foraminiferal response to pollution. The tests have been nalysed for living abundance, abnormal chamber growth and species dominance. Samples show the species *'aynesina germanica* (Ehrenberg) is dominant within the living and dead assemblages with a maximum 35% living. he species *Elphidium williamsoni* Haynes and *Ammonia beccarii* (Linne) each show a very low living abundance. iversity is low and only the Suborder Rotaliina is present with living representatives. Sample location, Tallack's Creek iows the highest abundance of living and living specimens with abnormal test structure. Tregunwith Wood shows a w abundance of living specimens and those exhibiting abnormal chamber growth. Both sides of the creek show a teral gradient with the frequency of test deformity decreasing away from the discharge point and a direct correlation xists between living deformed and undeformed.

Seasonal variation in agglutinated foraminiferan standing crops in the marsh and tidal flats of the River Erme, Devon

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ABSTRACT

A typical saltmarsh/tidal mudflat foraminiferal fauna has been identified in the Erme and clear zones have been defined. The high marsh is dominated by agglutinated taxa irrespective of the season, the transitional zone is only dominated by agglutinated taxa during the winter, the low marsh is dominated by calcareous species all year, and the tidal mudflat zone which is dominated by agglutinated species at the most elevated stations during the winter only.

Six euryhaline species have been identified, three agglutinated and three calcareous. Agglutinated taxa vary from 0-100% of the total foraminiferal standing crops depending upon elevation and season.

INTRODUCTION

The River Erme and other estuaries (see Fig. 1) have been selected to contribute control data in a pollution monitoring program using recent benthic foraminifera as indicators. The program was initiated in response to a large heavy metal discharge from Wheal Jane tin mine in January 1992, into the Carnon Valley (Fig. 1, box 3) river catchment which is already highly contaminated with metals from centuries of mining activity (Stubbles, 1993). As with several other river systems in S.W. England, the River Erme (Fig. 2) has been influenced by mining activity but to a lesser extent relative to the Carnon Valley (Bryan & Hummerstone, 1973a) and for a shorter duration. The Erme is, therefore, relatively unpolluted by heavy metals.

The Erme sample area is within a Site of Special Scientific Interest (SSSI) and is well conserved amid a region of arable and stock farming. Very little of the immediate area has been influenced by modern incursions, eg. residential and industrial expansion. The lower estuary area comprises sandy beaches, used for leisure and by holiday makers but it still remains relatively unspoilt.

The Erme is a ria and is macrotidal, deriving its water from Dartmoor to the north and several tributaries to the NE and NW, which ultimately flows into the English Channel. Freshwater flow varies both with season and rainfall, and, as a result salinity has widely varying ranges. Surface salinity in the high marsh area varies between 5 parts per thousand (‰) in the winter to 26‰ in the summer. The low marsh area may reach values approaching normal marine (32‰) in the summer, falling to 20‰ in the winter. A recent variable depth salinity survey has shown that the Erme is stratified with a saline wedge. During the ebb tide the channel narrows to less than 5m in the sample area, exposing extensive mudflats which grade from muddy-sand below Efford, sandy-mud at Efford and a mud-silt at Holbeton Point (Fig. 3).

METHODS

Standard intertidal sampling and processing methods have been used (see Stubbles, 1993). The same methods of collection and processing have been applied to all the estuaries featured during this current program with the same unit area, 78 cm^2 of material being removed for foraminiferal analysis. An additional sample is also collected for geochemical analysis, at seasonal time intervals. The Rose Bengal staining method (Walton, 1952) has been used with red stained individuals being regarded as living or only recently dead at the time of collection. Sample splits have been picked and analyzed for absolute and standing crop data. The standing crop values have been normalised to $10cm^2$.

FIELD DESCRIPTIONS

Two traverses, one each on the west and east sides of the Erme, comprising 19 stations have been sampled during the winter (January), spring (April), summer (July) and autumn (November) of 1993 (Figs. 4-7).

In: Kaminski, M.A. Geroch, S., & Gasiński, M.A. (eds.) 1995. Proceedings of the Fourth International Workshop on Agglutinated Foraminifera, Kraków Poland, September 12-19, 1993. *Grzybowski Foundation Special Publication* no. **3**, pp. 265-270.

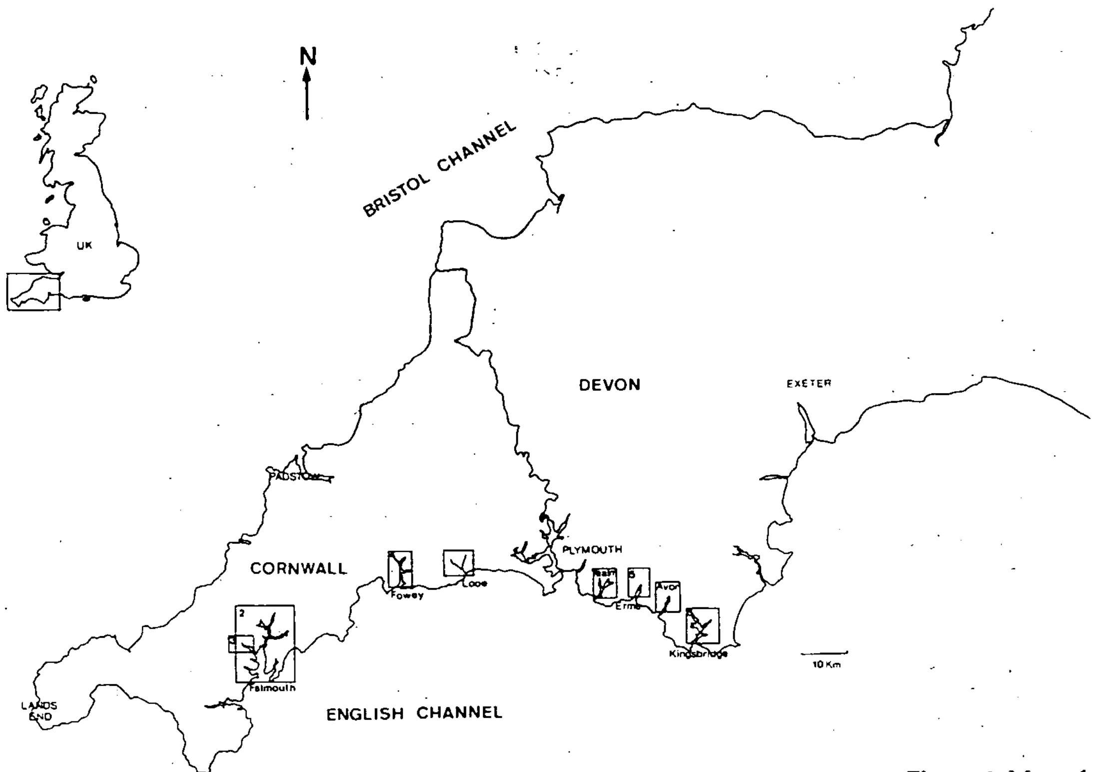

Figure 1. Map of the southwest of England, showing the sampled localities.

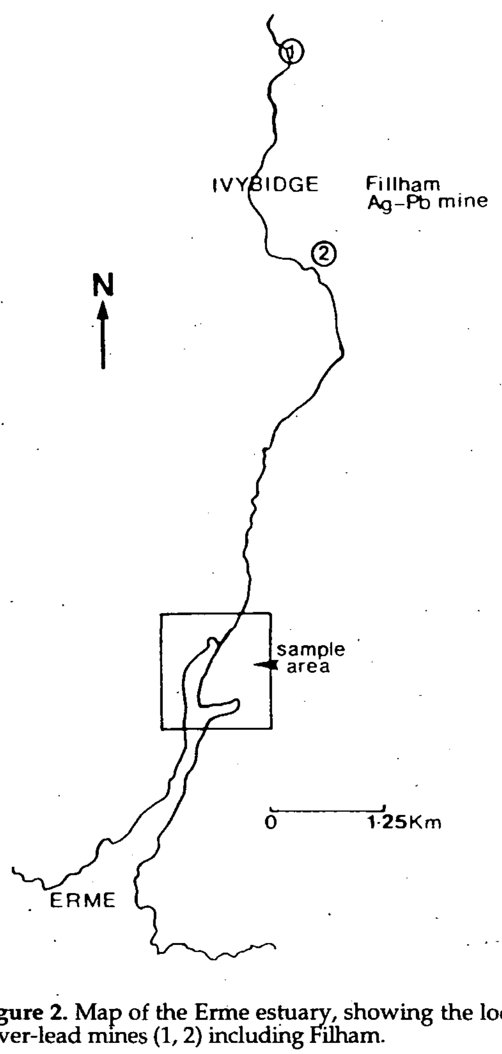

Figure 2. Map of the Erme estuary, showing the location of silver-lead mines (1, 2) including Filham.

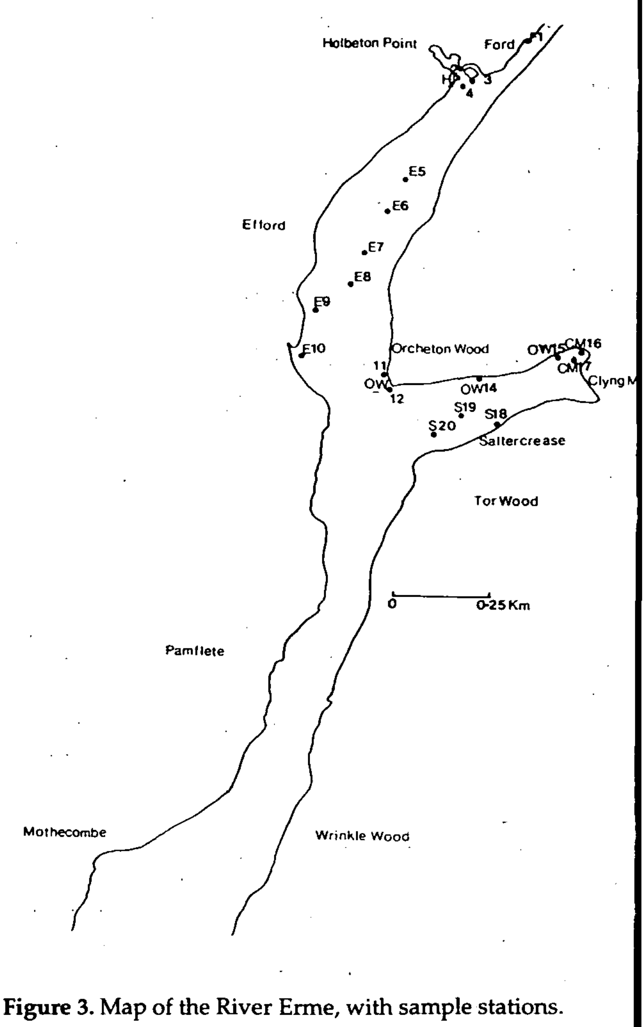

Figure 3. Map of the River Erme, with sample stations.

Traverse 1. Station F1 (Ford) is within the main channel. There is a paucity of substrate and no living foraminiferans have been found (Fig. 3). Station HP2 (Holbeton Point) has been colonised by *Spartina anglica, Phragmites communis* and *Puccinellia maritima* marsh flora, forming large raised areas enclosing salt pans of mud and sandy-mud. Station HP3 is a similar environment to station HP2 but is nearer to the main channel, approximately 1m away. Station HP4 is also near the main channel but 0.5m downstream of an outfall removing treated sewage from the small sewage works at the village of Holbeton. Muddy substrate predominates. Stations E5/E6/E7/E8 (Efford) are within open mudflat partially colonised by *S. anglica* and *Halimione portulacoides* marsh raised above the substrate. The substrate is of sandy-mud with abundant shell debris. Stations E9/E10 have isolated areas of *S. maritima* and *H. portulacoides* marsh as raised hummocks with coarse grass. These stations are proximal to the freshwater pond. The substrate is sandy-mud and muddy-sand with abundant shell debris. A muddy-sand bar separates these stations from the main channel.

Traverse 2. Stations OW 11/12 (Orcheton Wood) are proximal to the *S. maritima* and *P. maritima* coarse grass bank. The substrate is sandy mud. Stations OW14/OW15 are within the small mudlfat creek known as Clyng Mill. The stations are situated close to the rocky shore with saltmarsh flora being completely absent. The substrate is sandy mud. Stations CM16/CM17 are at the head of the creek below the wall and coarse grass bank separating the mudflats from the disused trout ponds at Clyng Mill Cottage. The substrate is mud. Station S18 (Saltercrease) is on the south side of the creek within the tidal mudflat. There is a mud substrate adjoining a coarse grass bank of *P. maritima* and *Aster*. Station S19 is half way between the grass bank and the stream channel within the tidal mudflats. The substrate is of sandy mud. Station S20 is beside the garden to Saltercrease House and adjacent to a coarse grass bank of *P. maritima* and *Aster*. The substrate is sandy mud.

RESULTS

Traverse 1. No living foraminiferans have been found at station F1. Stations HP2, HP3 and HP4 are generally impoverished and living specimens occur only during the winter, spring and autumn (Tables 1a-d; Figs. 4, 5, 6, and 7). The agglutinated foraminiferan *Millammina fusca* (Brady 1870) comprises 100% of the standing crops at these stations, except at HP4 in the spring, when *Elphidium williamsoni* Haynes 1973, dominates the fauna (Fig. 5). The agglutinated species present *Jadammina macrescens* (Brady 1870) and *Trochammina inflata* (Montagu 1808), are only present in very small numbers during the spring and autumn (Tables 1b and 1d). The calcareous species *Haynesina germanica* (Ehrenberg 1840) is also rare. Generally, average standing crops at these high marsh stations are lower than elswhere c. $45/10cm^{-2}$ (Figs. 4, 5, 6 and 7).

Millammina fusca is the dominant species at stations E5 and E6 during the winter and at E6 in the summer (Tables 1a and 1c). During the other seasons *M. fusca* is rank ordered second after *E. williamsoni*. As at other stations the other agglutinated species are present in small numbers and do not exceed $4/10cm^{-2}$. *H. germanica* is ranked third. *Ammonia beccarii* (Linné 1858) is present in sample E5 during the winter, spring and summer but occurs nowhere else in traverse 1.

At station E7, *M. fusca* is ranked second to *E. williamsoni* during all seasons, but they have relatively similar standing crops in the summer (Fig. 6). At station E8 *E. williamsoni* dominates throughout the year, with *M. fusca* ranked second except in the autumn when *H. germanica* is ranked second. *T. inflata* is absent in all E8 samples, but is present in the E7 summer sample. *Jadammina macrescens* is present in the winter and autumn E8 samples, but is absent in the sample E7 for all seasons.

Millammina fusca is ranked second at station E9 except in the autumn, when it is ranked sixth (Table 1d). At station E10, *M. fusca* is only ranked second in the spring. In the summer and winter, *M. fusca* is ranked third after *E. williamsoni* and *H. germanica*, and is ranked fourth in the autumn (Table 1d). The standing crops of *J. macrescens* and *T. inflata* rise at these stations, particually in the winter and autumn.

Traverse 2. At stations OW11 and OW12, combined standing crops of the calcareous species dominate the fauna during all seasons (Figs. 4, 5, 6 and 7). *Millammina fusca* is ranked second in the winter and spring only. It is ranked third after *H. germanica* in the summer, and is absent altogether during the summer and autumn at station OW11. At OW12 it is absent during the autumn. *J. macrescens* and *T. inflata* are extremely rare in all the seasonal samples, not exceeding more than 8% in the winter and 4% in the autumn of the combined agglutinated species standing crops. *Ammonia beccarii* is less rare at stations within traverse 2. At OW11, it is present in the winter, spring and summer and at OW12 is present in the autumn only.

In the winter sample at OW14 *M. fusca* is the dominant species. During the other seasons it is ranked third after the indigenous calcareous species and is absent in the autumn sample, with *A. beccarii* ranked third. *Ammonia beccarii* is generally a minor species and is absent during the winter but it is present in the spring at OW15 and in the autumn at OW14. *J. macrescens* and *T. inflata* are absent in all the OW14 and OW15 seasonal samples. *Millammina fusca* is rank ordered second at OW15 during the winter but otherwise is ranked third after *E. williamsoni* and *H. germanica*.

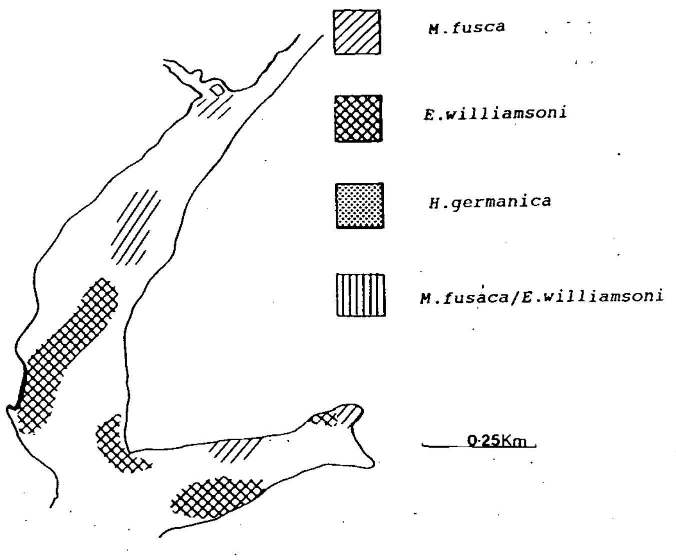

FIG.4: Species dominance during the winter.

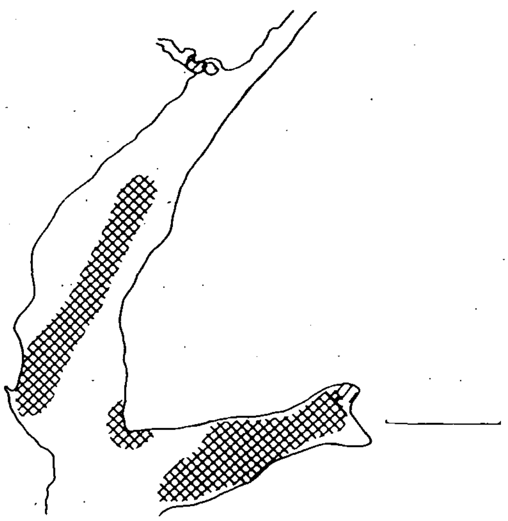

FIG.5: Species dominance during the spring.

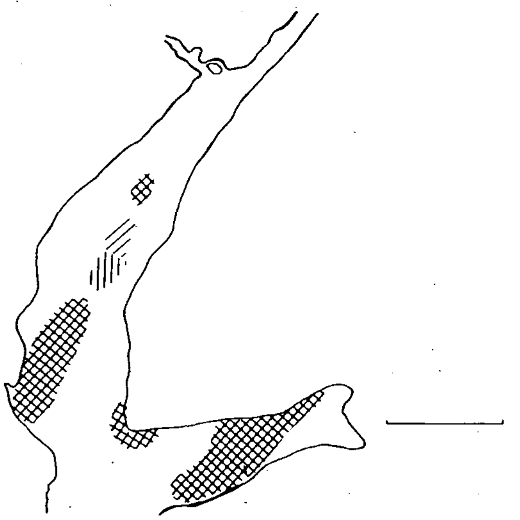

FIG.6: Species dominance during the summer

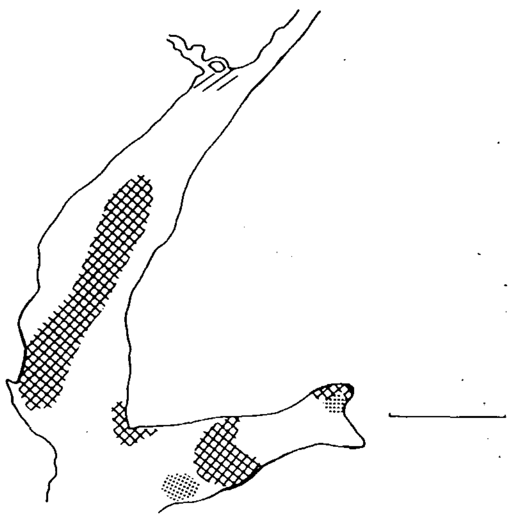

FIG.7: Species dominance during the autumn

Millammina fusca is the dominant species during the winter and spring at station CM16 and is also dominant at CM17 in the winter. At station CM17, *M. fusca* is ranked third during the spring and autumn. No living *M. fusca* were found in the autumn CM16 sample, and only $4/10cm^{-2}$ have been collected from the CM17 in the autumn sample. *J. macrescens* is the only agglutinated foraminifera in sample CM16/autumn and accounts for just 7% of the agglutinated species at this station in the winter. *Trochammina inflata* and *A. beccarii* are absent at these two stations.

Millammina fusca is ranked third at S18 in the winter, spring and autumn. It is second at stations S19 and S20 in the winter and fourth at S18 in the summer. At stations S19 and S20, *Millammina fusca* is ranked third. *Trochammina inflata* is present in the summer and autumn samples of station S20, comprising 14% and 50% respectively of the combined standing crops of agglutinated taxa. *Ammonia beccarii* is present in the spring and summer samples from station S18.

SUMMARY

Faunal zonation and seasonal variation in standing crops. The absence of foraminifera at station F1 is consistent with the results of the preliminary investigation carried-out in July 1991, and no extraordinary significance is attached to this. The most reasonable conclusion accounting for this absence are the extremes in environmental conditions which are of lethal levels. Stations HP2, HP3 and HP4 comprise a predominately agglutinated taxa, which is very patchy. The dominance of the marsh indicator species *M. fusca* (Alve & Murray, 1994) defines a high marsh environment during all seasons, which extends in the winter into stations E5 and E6. The distribution of predominately calcareous species at stations E5, E6, E7 and E8 defines a transitional marsh environment. The second and third rank order (depending on the season) of *M. fusca* at E9, E10, OW11 and OW12 suggests a low marsh environment. The tidal flat environment of Clyng Mill has a predominately calcareous species distribution during all seasons except in the winter at CM16 and CM17, which are dominated by *M. fusca* and, therefore, is a transient high marsh/low marsh environment (Phlegler, 1970).

Averaged standing crops of *M. fusca* and *E. williamsoni*, vary seasonally throughout the sample area. The winter sample shows *M. fusca* ($61/10cm^{-2}$) and *E. williamsoni* ($66/10cm^{-2}$) to have near identical standing crops but in the other seasonal samples the difference in standing crop values becomes more pronounced: spring $42/10cm^{-2}$ to $112/10cm^{-2}$; summer $22/10cm^{-2}$ to $87/10cm^{-2}$; and autumn $19/10cm^{-2}$ to $71/10cm^{-2}$ for *M. fusca* and *E. williamsoni* respectively. This suggests *M. fusca* is a winter opportunist responding to reduced competition caused by the dormancy of the calcareous species which bloom in the spring and summer.

The standing crops of the species *M. fusca* are greatest during winter and spring in the environments of the high/saltmarsh and at stations E5 and E6 in the transitional marsh environment. During the summer and autumn, *M. fusca* is a minor component of the assemblages present in the low marsh and tidal flat environments. The agglutinated species *J. macrescens* and *T. inflata* have higher standing crops, ranking higher or equal to the standing crops of *M. fusca*.

CONCLUSIONS

The euryhaline species present in the River Erme form characteristic hyposaline/ brackish/ hypersaline faunal environments of high marsh, transitional marsh, low marsh and tidal mudflat. There is a general decrease down estuary of the foraminiferan *M. fusca*, but improved standing crop populations of *A. beccarii*, which has narrower tolerance thresholds relative to the other indigenous species. *M. fusca* remains, however, a common species. *M. fusca*, with its characteristic wide tolerance thresholds, appears to be an opportunist more suited to the elevated areas of maximum exposure and drying times which exist in the saltmarsh and, also occurring during periods of dormancy of the calcareous species.

The high variation in standing crops, in particular the rarer species, may be due to clumping (Murray, 1991) and the formation of foraminiferal micro-environments. Scott & Leckie (1980), however, suggest that the patchiness shown by marsh foraminiferans is systematic of year to year environmental variables which can only be delimited by extensive and continuous sampling over a number of years.

The findings of the Erme estuary investigation are consistent with sample data from the Fowey Estuary, presently being analyzed (Fig. 1). The Fowey sampling program is as yet incomplete but initial results show similar faunal zoning with patchiness being evident in the winter and spring. Continuous sampling will contribute sufficient data to delimit natural environmental variables and isolate metal pollution controls on foraminiferal species distribution, test condition and standing crop numbers.

ACKNOWLEDGEMENTS

I would like to thank Dave Peacock for reading and correcting this manuscript, and for the cryptic drawing. I am grateful to Mr. Mildmay-White of the Flete Estate for allowing me unlimited access to carry-out my sampling. The support given by my supervisors Professor Malcolm Hart, Dr. Colin Williams and Dr. Steve Casswell, and, the staff of the department is much appreciated. My thanks also go to Mike Kaminski for his support and assistance. I also wish to thank the Committee of the Harold Hyam Wingate Foundation for their good wishes and financial support in the pursuance of a PhD. Finally, I thank my family for their continued support and patience.

I dedicate this paper to the memory of my recently deceased supervisor Steve Caswell. He played a major supportive role as my undergraduate supervisor and continued to influence the quality of my research work.

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Tables 1a-d. Standing crops of indiginous species / 10 cm^3 (except those marked by an * which denotes total live individuals.

1A winter

Species	Stns.	HP2	HP3	HP4	E5	E6	E7	E8	E9	E10	OW11	OW12	OW14	OW15	CM16	CM17	S18	S19	S20
H.germanica		0	0	0	0	4	0	16	31	11	5	0	24	50	17	4	41	0	0
E.williamsoni		0	0	*2	34	90	73	59	93	117	101	181	48	124	46	72	102	84	29
A.beccarii		0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0
M.fusca		0	78	15	224	124	55	31	33	6	25	25	72	66	78	280	17	14	14
J.macrescens		0	0	0	*3	0	0	4	4	3	1	0	0	0	6	0	0	0	0
T.inflata		0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0

1B spring

Species	Stns.	HP2	HP3	HP4	E5	E6	E7	E8	E9	E10	OW11	OW12	OW14	OW15	CM16	CM17	S18	S19	S20
H.germanica		1	0	3	21	8	41	18	27	6	28	10	68	53	14	53	96	21	14
E.williamsoni		1	0	23	228	124	158	106	173	39	186	46	251	117	44	190	227	135	73
A.beccarii		0	0	0	0	0	0	3	5	0	3	0	0	3	0	0	19	0	0
M.fusca		71	0	0	137	69	114	54	71	32	74	12	14	10	51	32	35	14	8
J.macrescens		1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
T.inflata		1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0

1C summer

Species	Stns.	HP2	HP3	HP4	E5	E6	E7	E8	E9	E10	OW11	OW12	OW14	OW15	CM16	CM17	S18	S19	S20
H.germanica		0	0	0	8	10	17	33	16	14	43	105	107	77	n/d	n/d	68	62	31
E.williamsoni		0	0	0	45	51	54	607	4	35	133	48	135	25	n/d	n/d	105	197	37
A.beccarii		0	0	0	0	0	0	8	21	0	4	0	0	0	n/d	n/d	12	0	0
M.fusca		0	0	0	39	80	58	107	0	6	0	33	21	8	n/d	n/d	8	0	12
J.macrescens		0	0	0	0	0	0	0	0	0	0	0	0	0	n/d	n/d	0	0	0
T.inflata		0	0	0	4	0	4	0	0	0	0	0	0	0	n/d	n/d	0	0	2

1D autumn

Species	Stns.	HP2	HP3	HP4	E5	E6	E7	E8	E9	E10	OW11	OW12	OW14	OW15	CM16	CM17	S18	S19	S20
H.germanica		0	0	0	34	25	27	29	29	12	26	8	96	8	12	13	8	20	37
E.williamsoni		0	0	0	136	125	68	80	121	21	84	181	162	121	19	11	104	89	12
A.beccarii		0	0	0	0	0	0	8	21	0	0	8	12	0	0	0	0	0	0
M.fusca		0	107	29	108	25	43	21	1	6	0	0	0	4	0	4	1	8	2
J.macrescens		0	4	0	0	1	0	4	4	8	0	0	0	0	2	0	0	0	0
T.inflata		0	0	0	0	1	0	0	8	1	0	0	0	0	0	0	0	0	2

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Responses of foraminifera to presence of heavy metal contamination and acidic mine drainage

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Abstract

Pollution monitoring using the responses of recent benthic foraminifera as primary indicators can be used to determine the impact of past, present and future contamination and possible remedial action. The use of benthic foraminifera as indicators is an inexpensive and reliable method easily applied to marine and estuarine ecosystems. Specific responses to heavy metal pollution are low diversity, low standing crops, high frequency of deformed tests and acid etched tests.

Following the major discharge of January, 1992 into the Carnon river and Restronguet Creek from the Wheal Jane tin mine in south west Cornwall, a pollution monitoring and research programme was inaugurated using benthic foraminifera. Investigations of foraminiferal responses to heavy metal pollution had not been carried-out prior to the discharge and, therefore, no foraminiferal comparative data base exists. Following sustained periods of acidic (pH 2.5) and metalliferous water drainage from subsurface mining activity the sediment remains acidic and enriched with heavy metals. Coring has shown, that as a consequence of the acidity, there exists an inverse relationship between increasing depth and a decrease in the number of specimens present, and below 15cm no foraminifera have been found, suggesting complete dissolution of the foraminifera. In order to determine background levels of foraminiferal responses and constrain interpretations typical of the SW metalliferous region, control estuaries have been selected. The comparative estuaries sampled so far, Fowey (south west Cornwall), Avon and Erme (south west Devon) drain once active mining districts though were relatively small enterprises compared with the Carnon Valley and work ceased in the last quarter of the last century. Readjustment of the ecology of these estuaries is thus implied. In contrast, Wheal Jane ceased active mining in 1991.

A three year period of sampling has documented the following improvements in Restronguet Creek; population of previously barren stations, higher standing crops, a reduced proportion of deformed tests and less severe acid attack on the test wall. Deformed foraminifera in the Restronguet Creek samples now average 7%, in a range from 1% to 9% (the highest values and lowest standing crops are found nearest to the Wheal Jane discharge point). The threshold level, defined by the control estuary samples, is 3%. Water pH now ranges in Restronguet Creek from pH 6.3 at Devoran to 8.0 at the mouth. Water pH in the control estuaries is either neutral or alkaline. The boundary line separating acute acid test dissolution from less acute has retreated towards the stations in the upper creek nearest to the point of discharge. These improvements suggest that tangible benefits have been gained by the liming

and primary settlement treatment of contaminated mine water. Low diversity, however, remains unchanged and the agglutinated species typical of tidal mudflats and saltmarshes and present in the control estuaries, have not populated the contaminated site.

Geochemical analysis of sediment samples taken from the three estuaries correlates with the foraminiferal data and the level of mining influence. The concentrations of available metals in Restronguet Creek are one order of magnitude higher than in the Fowey and two orders of magnitude higher than in the Erme. With respect to Restronguet Creek, however, it is apparant that sediment bound heavy metals are not the primary source influencing foraminiferal response to pollution but is the pH and metal concentrations in the discharged mine water which are the primary controls.

The extent to which these improvements are sustainable depends upon continued mine drainage treatment and rain water recharge levels. During prolonged periods of rainfall, contaminated water is discharged untreated and as a consequence foraminiferal standing crops and the abundance of deformed tests tends to vary.

Introduction

Foraminifera as Indicators of Pollution

The specific use of benthic foraminifera as indicator organisms is a relatively new approach in the evaluation of pollution effects upon the environment and much of the early work concentrated on changes in the fauna in response to sewage (Resig, 1960[1]; Watkins, 1961[2]). More recently Alve (1991[3], 1995[4]), Alve and Nagy (1989[5]), Ellison and others (1986[6]) and Shariffi and others (1991[7]), have shown that foraminifera are reliable indicators of heavy metal pollution. The review by Alve (1995[4]) has shown that many forms of contamination, for example the discharge of paper/wood pulp, hydrocarbons (Vérec-Peyré, 1984[8]), thermal and sewage discharges, in addition to heavy metals, can produce distinctive reactions by foraminifera. As biomarkers of heavy metal pollution, they provide specific responses; low diversity, faunal shifts, lower standing crop (living), elevated abundance of deformed tests, higher metal concentrations in the protoplasm of individuals with deformed tests relative to undeformed and acid etching of the tests. This is a significant feature of foraminifera in a river system draining acidic mine waters. In this report we present observations on the changes in the benthic foraminifera of a Cornish creek following a major discharge in January, 1992, of water containing high concentrations of heavy metals.

The use of benthic foraminifera as indictors of heavy metal pollution has not previously been applied to any of the sample sites. As there is no comparative, pre-discharge data from the recently contaminated site, Restronguet Creek, and no pre-discharge reference point has been established by coring, other estuaries known to have drained once active mining districts have been used to define base limits of pollution effect. The Fowey (SE Cornwall), Erme and Avon river estuaries (SE Devon) have, therefore, been selected as controls and the data derived from these samples will delimit the anthropogenic influence of the polluted site. Seasonal samples have been taken from Restronguet Creek since October 1992 and the other estuaries over a full year from January 1993.

Study Area and Mining Background

The intertidal estuaries areas comprise a mixture of tidal mudflat and saltmarsh. Restronguet Creek (Figure 1) is predominately tidal mudflat. With respect to Fowey the sample stations are exclusively tidal mudflats (Figure 2). The Avon and Erme estuaries (Figures 3 and 4) are a mixture of mudflats and saltmarsh, with the latter occupying discrete areas in the upper to central areas sampled (Stubbles, 1995[9]). The estuaries are macrotidal rias and within the sample areas sampled the salinity gradients vary from 0-33‰ in the winter and 8-35‰ in the summer (Stubbles, 1993[10] and 1995[9]). Temperature gradients are also evident and surface temperatures vary from 4°C to 11°C in the winter and from 12°C to 18°C in the summer. The salinity and temperature gradients of the four sample sites and corresponding stations, are in general agreement. Sediment grain size varies between the sites and Restronguet Creek is predominately clay and silt, whereas the other sample sites contain moderate quantities of fine to medium sand and silt. It has been estimated that relataive to the other estuaries, the sediment in Restronguet Creek comprises 85% material of size<63 μm and 10% between >63 and <125 μm in size.

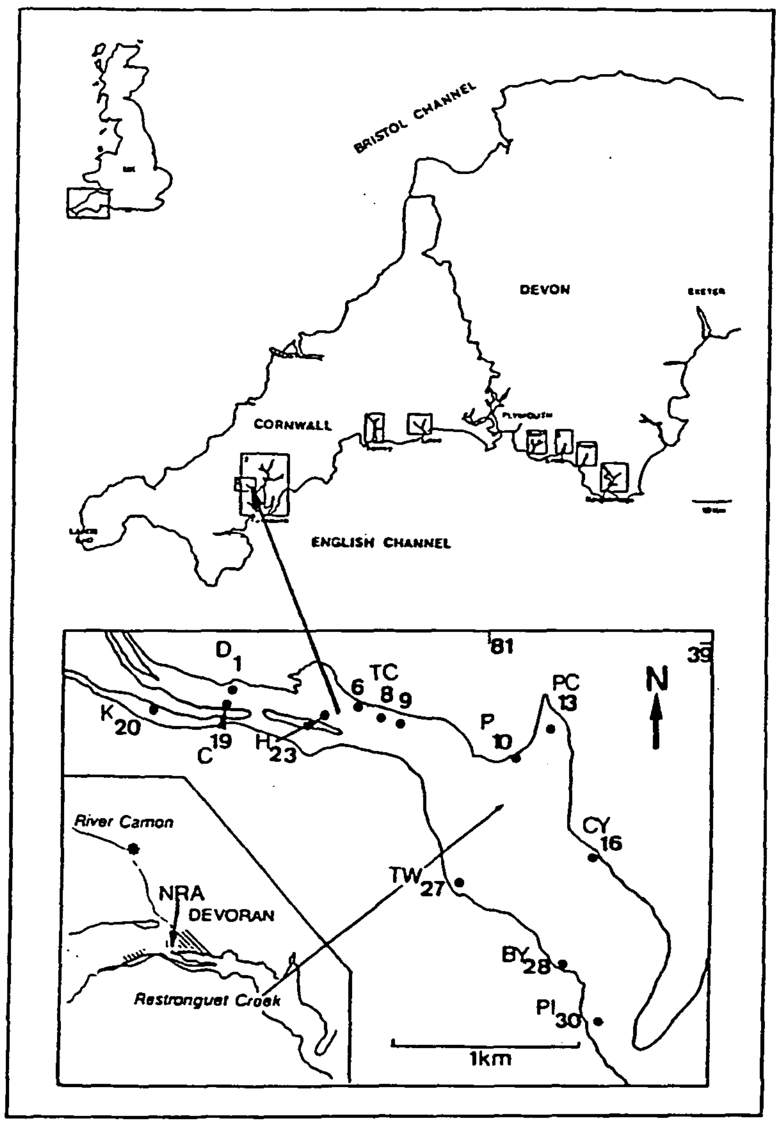


Fig.1 Maps of south west England (boxed areas refer to estuaries sampled) and Restronguet Creek and sample stations.

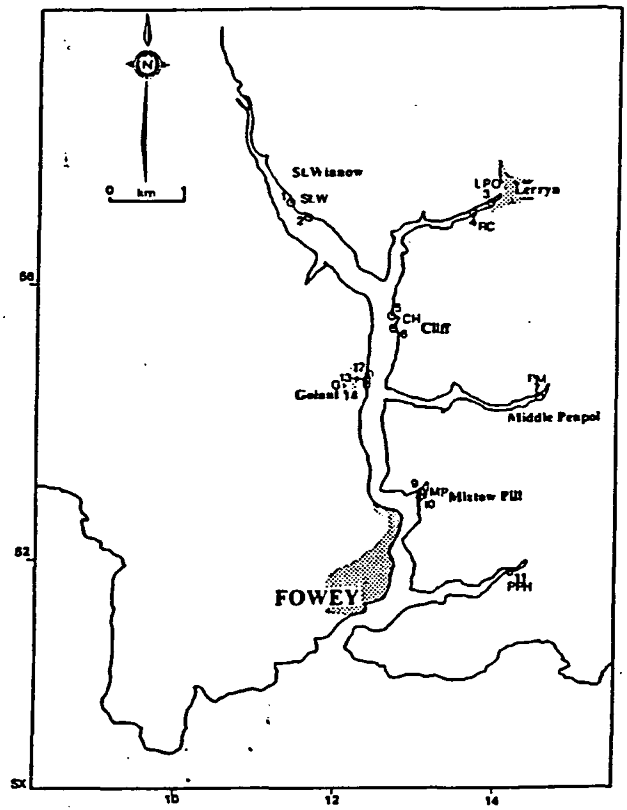


Fig.2 Map of the Fowey estuary sample.stations.

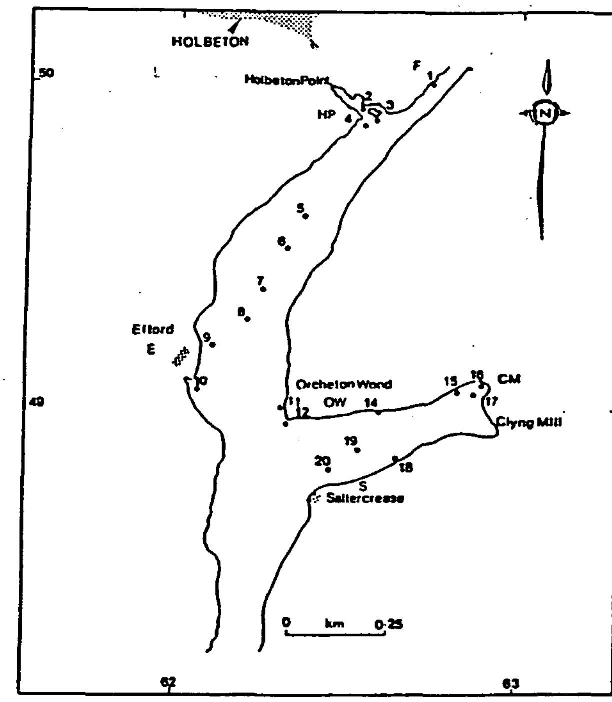


Fig.3. Map of the Erme estuary sample stations

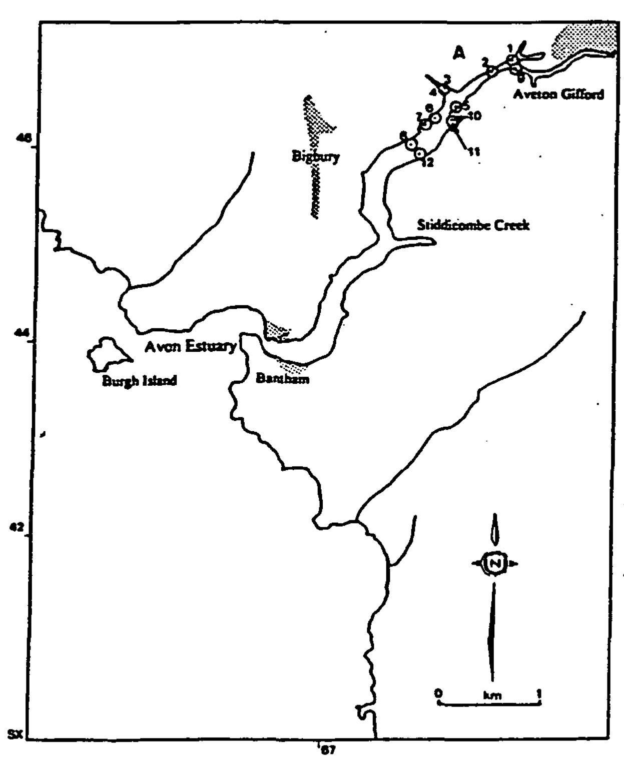


Fig.4 Map of the Avon estuary sample stations.

The pH of the water emanating from Jane and Nangiles adits (Figure 5) is c.pH 2.5 but on entering Restronguet Creek at Devoran road bridge, the pH is higher, varying from 3.8 to 6.3 at the Devoran sample station (D1) since sampling began.

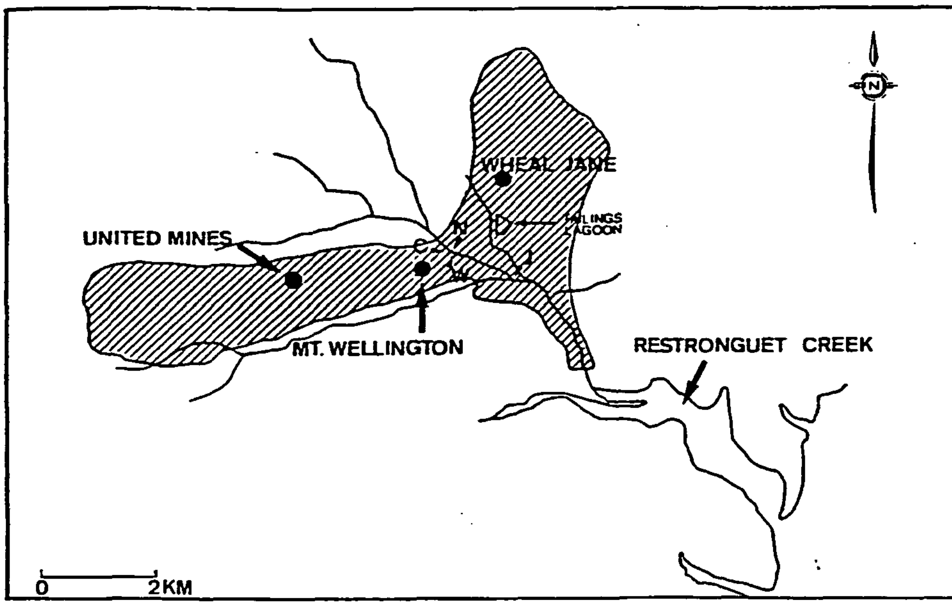


Fig.5 Map showing the Carnon Valley drainage catchment and the position of Wellington (W), County (C), Nangiles (N) and Wheal Jane (J) adits.

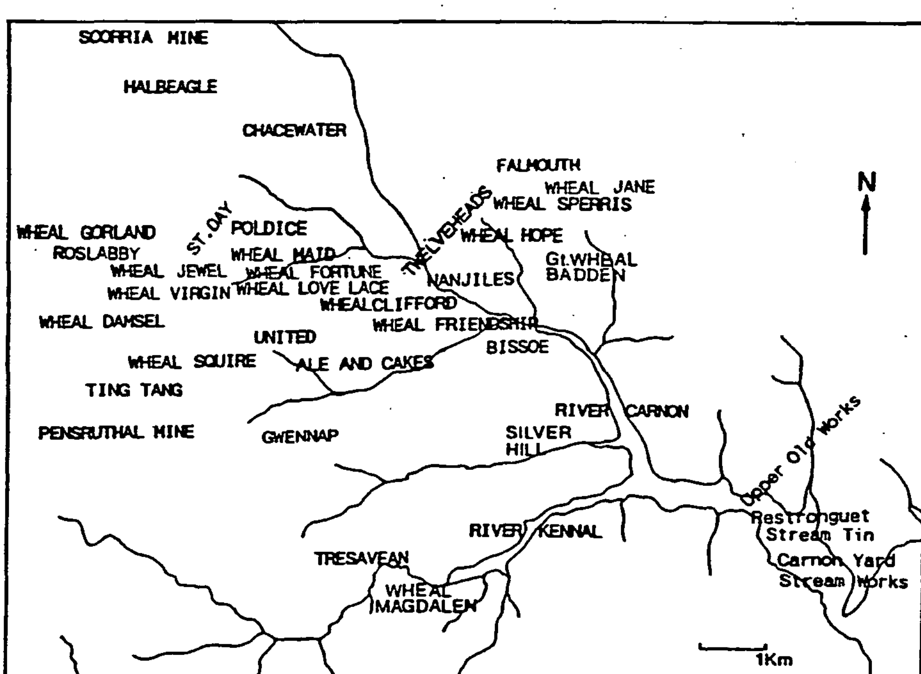


Fig.6. Mining area within the Carnon Valley catchment, showing the location of some of the better known old and recently worked mines.

Restronguet Creek and the other estuaries used in this research all drain previously active metal mining regions. Restronguet Creek, however, has been the site of widespread heavy metal discharge because of the lengthy periods of extensive mining affecting the Carnon Valley (Figure 6). The mines principally extracted tin, copper, silver and arsenic, with additional cadmium, lead, cobalt, nickel, zinc and uranite. The intensive, deep mining activity of the 18th and 19th century mining periods, was preceeded by centuries of shallow and streaming ventures. Cambridge (1995[11]) considered the shallow mine workings to have the greater impact on water quality. By 1890 a major decline in mining was a significant feature of the area (Barton, 1967[12]). Wellington and Wheal Jane mines were intermitently worked into this century but with the closure of Wheal Jane in 1991, all mining activity ceased in this once highly productive region of south west England.

The extensive discharge of January, 1992 from Wheal Jane has been related by The Carnon Update (1992[13]) and Cambridge (1995[11]). The combined treatment systems now inaugerated by the NRA and described by Cambridge, (1995[11]) have been put into effect. This treatment includes lime dosing and flocculant additive to increase pH and enable metal settlement in the tailings lagoon (Figure 5). In addition a passive treatment works has is also used but this accounts for only a small proportion of the contaminated mine water and forms a field laboratory (Cambridge, 1995[11]). These measures are being partially negated by contaminated drainage into the Carnon river and it's tributaries from ancient and old abandoned mines, and, the associated waste materials. There is also the potential for direct seepage into the river via the river bed which is close to the shallow workings connecting Wheal Jane and Wellington Mine.

Of the other estuaries sampled, the river systems draining into the Fowey estuary drained fewer mines than the Carnon Valley catchment and the Erme and Avon river systems, even fewer still. The Fowey catchment mining district drained large mine ventures; Lostwithiel Consols, Wheal Fortescue, Pelynwood, Wheal Howell and East Wheal Rashleigh (Hamilton Jenkin, 1967[14], Burt and others, 1987[15]). These mines were extracting a variety of metals and minerals, for example, Ba, Cu, Ag, Pb, Mn, Fe, Ni, Co and Sb. The Erme drained three reasonably well documented but small mining ventures; Caton, alluvial stream works, Filham and Ivybridge Consols. As with the Huntingdon mine on the Avon (Butler, 1993[16]), silver-lead was extracted, in addition to some tin (Hamilton Jenkin, 1974[17]).

Methods

Contemporaneous samples have been taken for foraminiferal and geochemical analysis. Temperature and salinity have also been recorded for spring high tides just prior to the samples being taken at low water. Due to the shallow water conditions low water readings were not possible.

Methods for Foraminiferal Analysis

Prior to the main sample programme a preliminary spot sampling reconnaisance survey was carried-out for each estuary. This established the faunal distribution and absence/presence of foraminifera. Subsequent sampling of each location followed transects along each side of each estuary. The sample stations are given by Figures 1 - 4. The samples, of known area ($78cm^{-2}$), were preserved in buffered formalin and on return to the laboratory have been wet sieved on a 63µm to remove the fines. The residue was then transferred to bowls and rose Bengal added for 45 minutes to stain the protoplasm of living or only recently dead foraminifera at the time of collection (Walton, 1952[18]). The samples were again rinsed on a 63µm sieve to remove excess stain and the residue returned to bowls and oven dried at 60°C. The dried material was seived through a seive stack of mesh sizes 1mm, 500µm, 250µm, 125µm and 63µm and sub-samples of each fraction were picked from a gridded tray. Individual foraminifera were transferred to a lightly gummed, gridded slide for inspection and counting. The absolute abundance of living (standing crops) was then calculated.

Microprobe analysis

The summer 1992 seasonal data set was used for the microprobe analysis. As the stations C19, D1 and K20 were barren at this time no specimens from these stations could be included. Six stained individuals each of deformed and undeformed for each station were fixed in resin to give a total sample of 60 specimens per resin stub. The stubs were ground and polished to form a completely flat surface exposing the stained protoplasm. The Jeol 6100 was used to detect the elements present in the protoplasm. The test wall was avoided as this area is considered to be prone to metal absorption and this may not be related to metal accumulation within the organism.

Methods for Geochemical Analysis

Preliminary experiments using a single reagent extraction method have been carried-out on the sediment samples to determine bioavailable metal concentrations for three of the four locations and specifically to Restronguet Creek, the effects of low pH on metal reactivation and mobilisation.

Duplicate samples (1g dry weight) from each station were immersed in 10mls H_2SO_4, in centrafuge tubes at pH values of 2.5, 3.8 and 5.2 (diluted with deionised water). Each sample was placed in an ultrasonic bath for 15 minutes and the final pH value before filtration was recorded. The original solution values were reduced slightly after contact with the sediment and the final values were 2.5, 3.6 and 5.1 with a systmetic error of ± 0.1. The sample was then filtered into a volumetric flask containing 10mls of 5% HNO_3 to prevent metal adsorption to the glass. Frequent rinses with deionised water removed all the sample from the tubes and the solution made-up to 50mls with deionised water. In view of the fact that H_2SO_4 is the principle agent leading to metal mobilisation from the Restronguet Creek sediments, this acid was used in the experiment rather than buffered solutions (eg., phthalate), the method of Trefry and Metz (1984[19]).

The same ratios of sample to solution (10% HNO_3) were used in another experiment to determine leachable and therefore, available metals. This experienent was carried-out on all the samples from each location. Shorter ultrasonic periods of 5 minutes were applied to the sample immersed in a solution of cold 10% HNO_3 The sample was filtered with rinses of cold 10% HNO_3 to a final volume of 50mls. Flame AAS was used to determine concentrations of the metals; Zn, Cu, Fe, Cd, As, Al, Ni and Pb. Stoicheiometric standards were used to construct the calibration curves for each metal.

Results

Foraminiferal Analysis-Diversity

The three calcareous and three agglutinated species; *Haynesinca germanica* (Ehrenberg)=*Nonion germanica* Ehrenberg, 1840, *Elphidium williamsoni* Haynes, 1973 and *Ammonia beccarii* (Linné) Brunnich, 1772, and *Millammina fusca* (Brady)=*Quinqueloculina fusca* Brady, 1870, *Trochammina inflata* (Montagu) Parker and Jones, 1859 and *Jadammina macrescens* (Brady) Brönnimann and Whittacker, 1984 are the indigenous species found in the control estuaries. The latter three agglutinating species are absent in Restronguet Creek.

Species dominance is intimately connected to diversity as one species may be less tolerant to stress relative to another. It has been established from the Restronguet Creek data that *H.germanica* dominates all live seasonal assemblages in the upper estuary stations; TC6, TC8, TC9 and P10 (see Figure 1). The lower estuary stations; PC13, CY16, TW27, BY28 and PI30 (Figure 1) are dominated by *E.williamsoni* in the autumn and winter while *H.germanica* dominates there in the summer and spring. After the summer of 1994 the situation changed and seasonal shifts in faunal dominance resemble that shown for Fowey with the spring and summer live assemblages being dominated by *H.germanica* and the autumn and winter dominated by *E.williamsoni* throughout the estuary (Figure 2). *Haynesina germanica* only dominates the summer live assemblage at a few stations at the Erme (Stubbles, 1995[9]). *Elphidium williamsoni* dominates or co-dominates with *M.fusca* in the mid to lower estuary stations all year round (Figure 3). The Avon data collected so far shows a similar seasonal distribution. Recently aquired data for Restronguet Creek shows the minor calcareous species *A.beccarii* to be increasing and it dominated the live assemblage at BY28 in the autumn of 1995. The order of tolerance determined from this data is *H.germanica* > *E.williamsoni* > *A.beccarii*.

Low standing crop

Comparisons between like stations from the control estuaries to those in Restronguet Creek shows that standing crop values (per 78 cm^{-2}) are depressed (Figure 7). During the period of this study, however, population of the previously barren stations, D1, C19 and K20 in Restronguet Creek has occurred and from spring 1994 standing crops have increased at all stations throughout Restronguet Creek. The recorded increase in stained individuals at PI30 is from 1072 in 1993, to 2504 in 1995 (Autumn data). Similarly, an upper creek station at Tallack's Creek (TC6) has shown an increase in standing crops 1993 to 1995, from 142 to 1188 individuals.

The standing crop data from the control estuaries has shown that seasonal standing crops vary with fewer stained individuals present in the winter when reproduction is negligable and higher values in the spring, summer and autumn. The Restronguet Creek samples taken in 1995 from PI30, for example vary with 3280 stained individuals in the Winter and 10048 individuals in the Summer. The comparable stations from the control estuaries show a similar relationship between season and standing crop. Station G12 has 1100 stained individuals in the Winter (1995) and 2732 (1994) in the Summer.

The upper stations from both the control and polluted estuaries show similar relationships between standing crop distribution and distance up estuary. The higher abundances of stained individuals are found in samples from the lower estuary/creek stations. The upper estuary stations are generally one order of magnitude less than the corresponding low estuary stations. Figure 7 shows standing crop variation for the upper estuary stations TC6, OW11, CH5 and A5 relative to the lower stations TW27, E8, G12 and A7

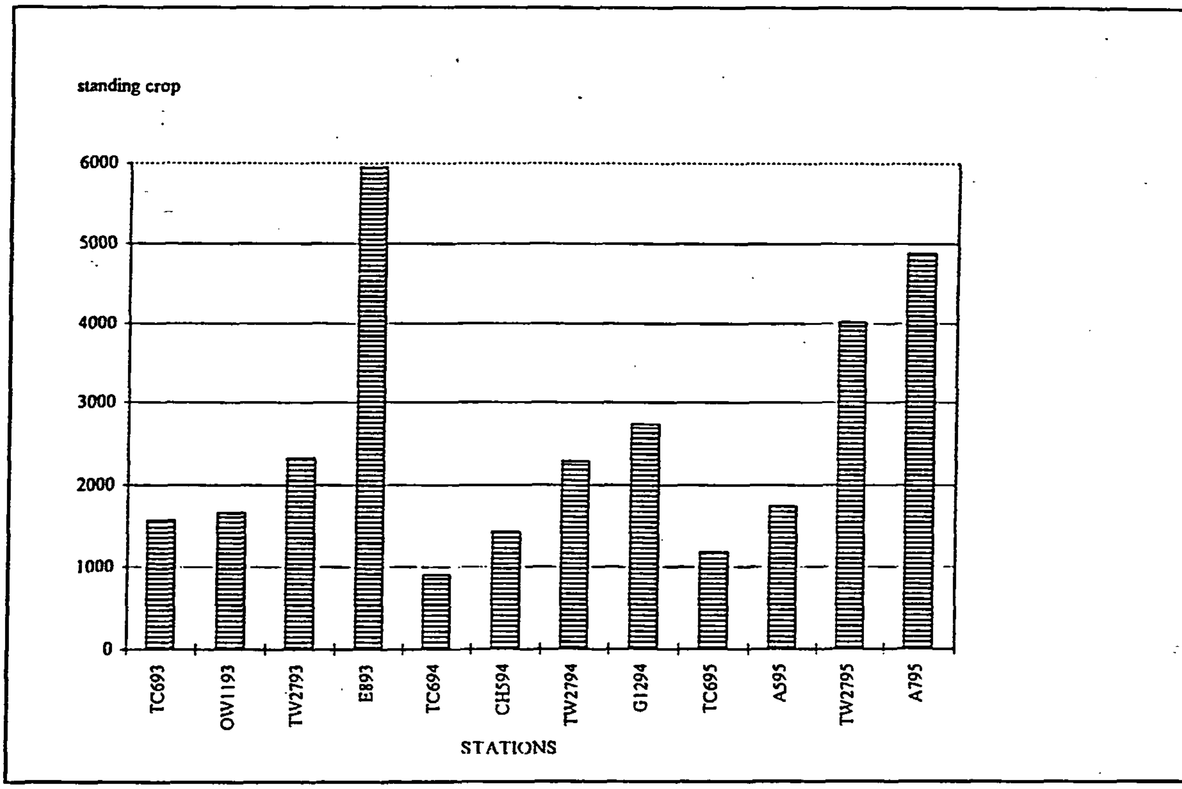


Fig.7. Graph showing the variation in standing crops between upper estuary stations, TC6, OW11, CH5 and A5 and the lower estuary stations, TW27, E8, G12 and A7.

Test Deformation

Plates 1 and 2 show examples of test deformity. Only the obvious aberrant forms are counted as deformed and the more subtle examples are considered to fall within the category of morphological variation. The abundance of test deformity from the control samples is <3% but the forms are similar to those found at Restronguet Creek. Samples taken from Restronguet Creek in July 1992 had abundances of 12% at PI30 and 25% at TC6 and a horizontal gradient is defined. The lower creek stations BY28 and PI30 have consistanly shown low % abundances of test deformity since the summer of 1994. The Restronguet Creek samples are currently (Autumn, 1995) between 1 and 9 %.

Metal Concentrations within the Tests

Preliminary results from the microprobe analysis have shown that the metals Al, Fe and Cu have been detected in the protoplasm in the deformed tests but not in the undeformed individuals (Figures 8 and 9). Zn was also found to be present in other examples but this metal is not shown by Figure 9. These initial results show that a qualitative pollution relationship exists between the deformed and undeformed foraminifera.

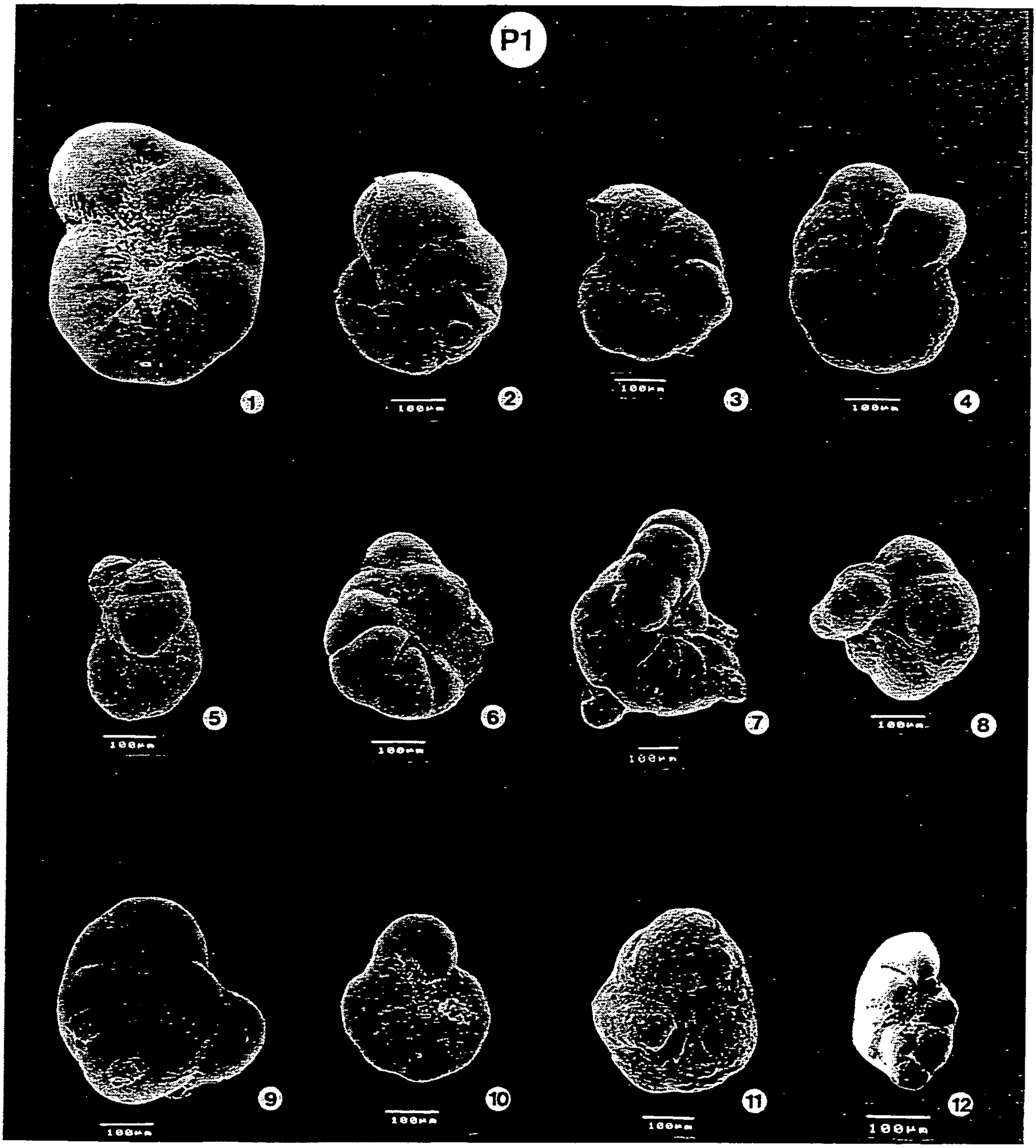


Plate 1. The forms of test deformity of the species *H.germanica.* SEM micrographs of, (1) type specimen, (2) enlarged last chamber and reorientated suture, (3) extension to chamber, (4) reduced last chamber relative to penultimate chamber, (5) additional chamber growth and enlarged last chamber, (6) additional chamber, (7) multiple chamber growth, (8) protruding additional chamber, (9) protruding additional chamber, (10) enlarged last chamber, (11) chamber overgrowth of the sutures, (12) test elongation and protruding chamber.

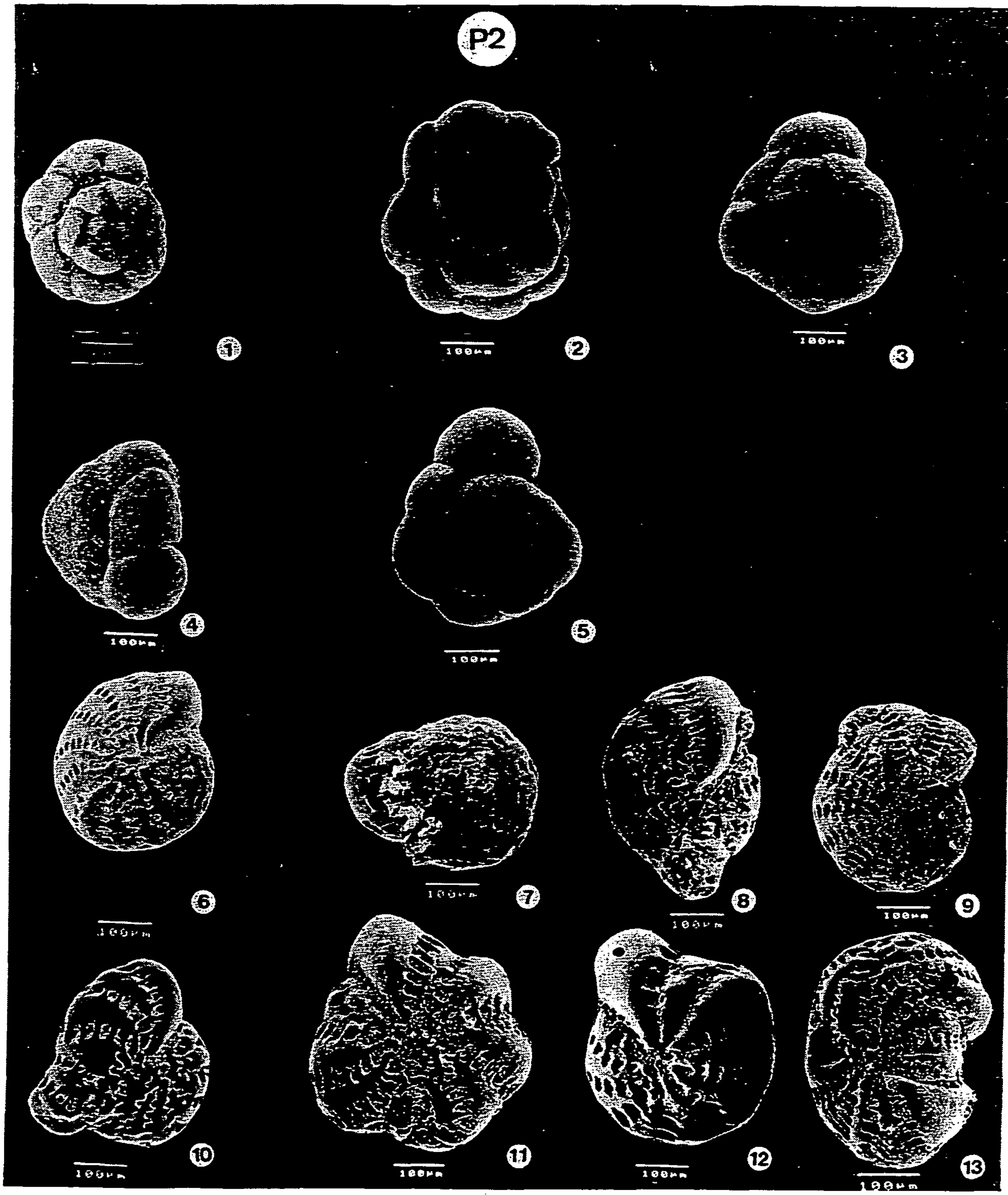
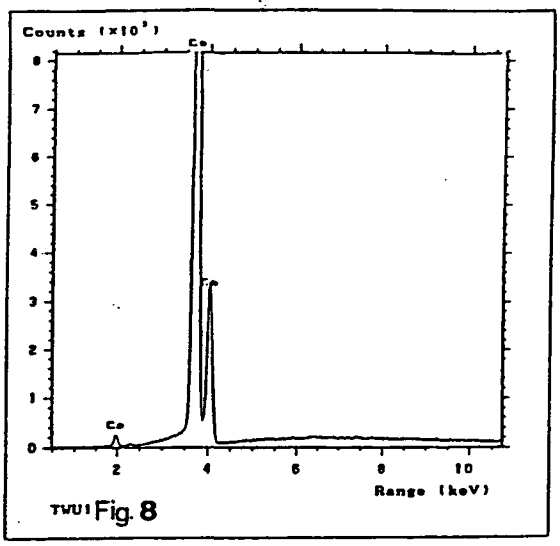


Plate 2. The forms of test deformity of the species *A.beccarii* (1-5) and *E.williamsoni* (6-13). SEM micrographs of, (1) type specimen, (2) twin-uneven chamber arrangement, (3) enlarged chambers, (4) high trochospiral proloculus, (5) enlarged last chamber, (6) type specimen, (7) prptruding chambers, (8) additional chamber growth, (9) reorientated suture, (10) protruding group of chambers, (11) daisy shaped test, (12) enlarged last chamber, (13) twin.



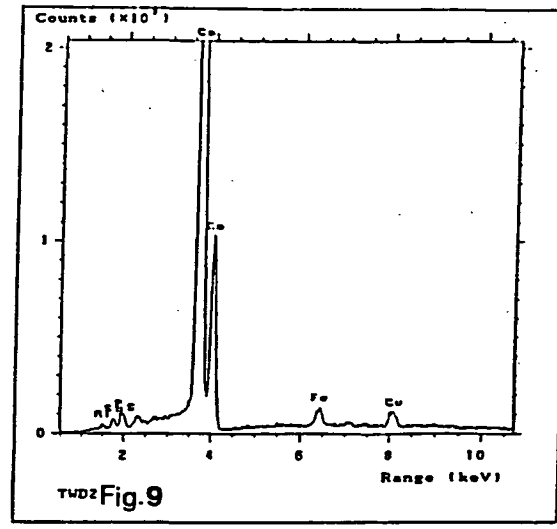


Fig.8. Microprobe analysis of undeformed tests. Spectrograph shows Ca is detected.

Fig.9. Microprobe analysis of deformed tests. Spectrograph shows Cu, Fe, S, P, Al, Si and Ca.

Acid Etching and Dissolution of the tests

The acidic conditions in Restronguet Creek have a severe affect on the foraminiferans in the upper and mid creek areas, with 100% of the stained individuals showing severe dissolution features. These features include calcified over apertures (which may be inferred to be a form of deformity) and the wall surface altered from glassy hyaline to an opaque white. The species *H.germanica*, *E.williamsoni* and *A.beccarii* are altered to produce a chalky white, granular internal texture and with occasional layering. *Elphidium williamsoni* appears to be more physically robust than *H.germanica*, the tests of which, in comparison, had been considerably weakened and are fragile by acid dissolution. The lower stations TW27, BY28 and PI30 were not affected by the acidic conditions. Those samples recently taken from stations previously affected (Autumn, 1995) show little opacity of the tests and are returning to the hyaline form.

Geochemical analysis

With respect to the pH experiments (Table 1) there is a steep decline in the concentration of metals mobilised with a rise in pH. The highest concentrations were achieved at pH 2.5 which were markedly greater than at pH 3.8 and 5.2. The two higher pH values produced concentrations of the same order of magnitude for Zn, Cu and Fe.

The data, shown by Tables 2, 3 and 4 was obtained from the available metal experiment. The three locations show that Restronguet Creek available metal concentrations is, generally, two orders of magnitude higher than in the Erme and one order of magnitude higher than in the Fowey. The lowest metal concentrations, with the exception of Cd, are found at CY16, BY28 and PI30 and the highest at C19 and K20 in the majority of examples. The highest metal concentrations for Fowey, Erme, and, the lowest for Restronguet Creek are compared as follows: Zn - G13/117 ppm, HP4/67 ppm and PI30/1634; Cu - G13/78 ppm, HP4/11ppm and PI30/220ppm; Pb - G13/62 ppm, HP4/45 ppm and TC6/ 55 ppm; Cd - G14/1.5 ppm, F1/0.7

ppm and D1/3.0 ppm; As - G13/20 ppm, S18/17 ppm and TC6 50 ppm. The Fowey data shows Al to be one order of magnitude lower than in Restronguet Creek and the Erme to be two orders of magnitude lower. The values for Fe are less easily compared but the concentrations found for the Fowey and Erme samples are lower than those recorded for Restronguet Creek.

A92	2.5*	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2
station	Zn	Zn	Zn	Cu	Cu	Cu	Fe	Fe	Fe	Pb	Pb	Pb	Cd	Cd	Cd	As	As	As	Ni	Ni	Ni	Al	Al	Al
D1	2361	19	11	871	18	15	503	59	45	5	2	0	3	0.2	0	12	12	12	6	0.8	0	851	35	25
TC6	2702	58	43	1031	30	29	893	73	70	9	0	0	4	0.1	0	41	0	0	7	1	0	1191	66	34
TC8	2739	47	3	1010	27	26	651	73	28	7	0.9	0	3	0.2	0	23	13	9	7	0	0	1033	53	9
TC9	2868	57	30	1156	28	29	937	91	71	8	0.9	0	3	0.1	0	19	14	11	7	1	0	1203	59	23
P10	1806	10	8	645	12	11	490	56	46	5	1	0	3	0.1	0	16	5	9	4	1	0	826	41	14
PC13	2120	29	21	493	23	18	752	72	69	12	1	0	4	0	0	25	6	9	6	1	0	789	55	22
CY16	2126	56	29	687	10	11	1130	79	27	11	1	0	3.5	0	0	27	10	7	4	0	0	886	74	11
C19	3044	n/d	17	1032	16	16	774	n/d	70	5	n/d	0	1.3	n/d	0	31	n/d	16	8	n/d	0	1393	n/d	16
K20	2988	17	18	1165	16	12	1434	49	43	6	0	0	1.5	0	0	30	11	9	7	0	0	1852	22	18
H23	2215	16	13	886	16	16	1210	78	61	6	0.8	0	2.7	0.1	0	31	16	4	5	0.8	0	975	48	25
TW27	1900	34	30	248	34	30	392	101	97	0	0	0	2.5	0.1	0	12	11	5	5	0	0	248	122	47
BY28	1365	23	18	159	15	13	514	83	74	2	1	0	2.7	0.2	0	18	5	11	1	1	0	329	67	22
PI31	238	n/d	5	52	32	26	180	n/d	21	1	0	0	0	0.1	0	12	n/d	10	1	n/d	0	119	n/d	16
A93	2.5*	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2	2.5	3.8	5.2
station	Zn	Zn	Zn	Cu	Cu	Cu	Fe	Fe	Fe	Pb	Pb	Pb	Cd	Cd	Cd	As	As	As	Ni	Ni	Ni	Al	Al	Al
D1	3887	131	78	1118	16	17	1172	36	34	21	0	0	2.4	0.3	0.25	27	14	0	9	0		1605	32	34
TC6	2666	47	37	921	28	22	679	62	40	15	0	0	1	0.33	0.12	12	0	0	6	0	0	1454	62	42
TC8	2676	55	34	1008	26	19	779	37	39	18	0	0	1	0.19	0.1	23	19	0	9	0	0	1150	34	29
TC9	2627	52	34	1072	27	20	894	65	46	20	0	0	0.9	0.23	0.13	34	12	0	7	0	0	1340	38	32
P10	1552	15	16	454	34	19	544	73	51	7	0	0	1	0.19	0.26	23	29	0	4	0	0	681	n/d	31
PC13	2155	n/d	19	781	28	n/d	833	n/d	80	23	0	0	1	n/d	0.4	13	n/d	0	5	0	0	1302	67	52
CY16	1492	14	14	397	36	23	442	68	42	9	0	0	1.3	0.12	0.3	n/d	0	0	3	0	0	649	51	56
C19	2632	89	50	916	20	16	666	71	49	10	0	0	1.5	0.13	0.12	31	26	0	6	0	0	1249	37	29
K20	2379	45	33	999	27	18	949	93	42	8	0	0	0.5	0.13	0.23	13	13	0	5	0	0	1449	40	32
H23	1155	34	16	435	16	8	831	111	43	22	0	0	0.9	0.25	0	10	37	0	3	0	0	886	34	29
TW27	1440	16	12	431	30	21	862	73	52	7	0	0	1.1	0.24	0	22	24	0	3	0	0	763	67	34
BY28	1105	14	15	286	39	25	381	125	54	2	0	0	0.95	0	0.15	0	0	10	4	0	0	538	62	48
PI30	954	13	9	97	30	26	292	59	40	15	0	0	0.97	0	0	12	0	0	4	0	0	380	62	24

Table 1. Concentrations of heavy metals (ppm) at pH 2.5, 3.8 and 5.2, for Restronguet Creek. The row marked with an * refers to the pH values.

Station	Zn	Cu	Fe	Pb	Cd	As	Ni	Al
D1A92	3234	1573	5448	105	2	197	23	2622
TC6	2900	1200	8134	55	1.5	5	11	2000
TC8	3900	1950	3382	130	2	125	23	3250
TC9	3697	1801	11956	123	2	142	21	2644
P10	3046	1571	4440	143	2.6	167	23	2380
PC13	2965	1215	4091	197	2.4	88	16	2187
CY16	2986	1098	4118	87	2	66	15	1976
C19	3737	1721	4277	75	1	91	19	3171
K20	3934	1269	4681	63	1	67	10	3040
H23	3360	1157	2494	154	2	240	14	3360
TW27	3432	866	4790	114	2.7	220	16	3992
BY28	2365	681	5100	88	2.6	86	10	2580
PI30	1634	220	5376	82	2	65	16	1935
Station	Zn	Cu	Fe	Pb	Cd	As	Ni	Al
D1A93	4449	1816	6660	132	3	100	25	4086
TC6	2984	1488	6566	119	2	75	24	2976
TC8	3108	1417	5760	101	2	101	19	2285
TC9	2138	1604	9700	141	1.5	107	27	3888
P10	1954	1066	13662	142	2	178	24	1776
PC13	3948	1315	12783	146	1.5	183	12	2192
CY16	2317	1373	5148	90	2	64	14	1931
C19	3913	1684	9758	114	2.5	68	25	3094
K20	2889	1693	5712	80	1.3	149	18	4731
H23	1634	860	N/D	90	0.7	86	9	1806
TW27	2695	1397	7889	90	1.5	100	20	2495
BY28	2300	1250	3704	88	2	150	19	2250
P130	1824	864	2160	86	2	120	15	2016

Table 2. Concentrations of bioavailable metals (ppm) for Restronguet Creek, autumn (A) 1992 and autumn 1993.

Station	Zn	Cu	Fe	Pb	Cd	As	Ni	Al
F1	37	6	1452	29	0.7	4	4	968
HP2	46	9	1175	29	0	16	4	710
HP3	49	10	1455	32	0	0	5	1364
HP4	67	11	1344	45	0	11	4	896
E5	39	7	1483	37	0	10	6	527
E6	35	7	1124	28	0	4	6	450
E7	39	8	723	36	0	8	12	497
E8	40	7	1615	34	0	11	15	574
E9	44	8	1780	36	0	7	14	579
E10	41	8	1688	38	0	7	15	570
OW11	33	8	1034	38	0	12	10	602
OW12	34	7	1067	34	0	8	12	524
OW14	34	8	796	35	0	0	19	530
OW15	31	6	909	36	0	0	15	432
CM16	55	12	2675	40	0	0	12	991
CM17	45	9	1890	32	0	0	8	630
S18	40	8	1494	35	0	17	9	523
S19	32	6	1277	27	0	0	10	447
S20	41	7	1368	32	0	4	11	529

Table 3. Concentrations of bioavailable metals (ppm) for the Erme estuary samples taken in the autumn 1993.

Station	Zn	Cu	Fe	Pb	Cd	As	Ni	Al
St.W1	99	62	1656	29	1	17	4	1035
St.W2	84	55	1686	19	0	13	6	1138
LPO3	66	19	1232	41	0	10	7	735
RC4	110	64	1737	33	0	9	6	1143
CH5	81	45	1263	29	0	9	5	631
CH6	64	33	1135	29	0	10	5	544
PM7	50	15	1801	26	0	19	6	602
MP9	70	38	1054	44	0	5	9	719
MP10	66	30	1091	37	1	10	5	546
PPH11	34	10	693	34	0	0	4	377
G12	78	36	1854	34	0	15	5	683
G13	117	78	1464	62	0	20	4	781
G14	95	47	779	18	1.5	20	7	496

Table 4. Concentrations of bioavailable metals (ppm) for the Fowey estuary samples taken in the autumn 1994.

Comparisons between the two data sets A92 and A93 show an increase in metal concentrations at some stations sampled in the autumn of 1993. These increases are generally limited to stations nearest to the discharge point, for example D1 with an increase of 1215 ppm Zn, 243 ppm Cu, 1212 ppm Fe, 27 ppm Pb, 97 ppm As, 2 ppm Ni and 1464 ppm Al. As these samples were analysed during the same run systematic error is not considered to account for the increases. Furthermore, duplicate samples show the same increase. The pH data also shows an increase in metal concentration between the 1992 and 1993 data sets and is, therefore, consistant with the available metal results.

Discussion

Low diversity is a feature of marginal marine environments (Alve and Murray, 1995[20]) and the six species present in the control estauries form a typical euryhaline suite. The absence of the agglutinated species is considered to be the result of heavy metal contamination as no other lines of evidence can account for this reduction in diversity. It may be suggested that the dissimilarity in grain size distribution between the polluted location and the control estuaries, is the controlling factor of this absence but other studies presently being investigated would not lend support to this. As there is no data before the discharge of 1992, it is not known if this absence of agglutinating foraminifera in Restronguet Creek is due to the most recent discharge or has prevailed uninterrupted through mining history. The occurrance of *E.williamsoni* at the upper estuary stations, as a dominant species in the winter and autumn (after the summer of 1994) suggests that this shift is co-incidental with the recorded lower concentrations of heavy metals in solution (pers. comm. R. Robinson, NRA and water quality data for 1994, NRA). Ellison and others (1986[6]) concluded that the retreat of intolerant species away from the source was a reaction to a point source pollutant and it would appear from the Restronguet Creek data that *E.williamsoni* is less tolerant of heavy metal pollution. Unlike the control estuaries which are zoned by the presence of the agglutinated species, there has been no down estuary zonation in Restronguet Creek since the summer 1994 and it is probable that the earlier formed zonation was controlled by heavy metal pollution. The recent improvement in the *A.beccarii* standing crop abundance, however, may be the result of the exceptionally long, hot summer of 1995 and it would be premature to attribute this change to improved water quality.

As the data from the control estuaries shows, standing crops and species dominance vary with season and distance up the estuary. Salinity, for example, is particually variable at the upper stations and is considered to be the cause of fluctuating and low numbers of living foraminifera (Alve, 1995[4]). Consequently, the standing crop gradient shown by the polluted site and control estuaries is a naturally occurring phenonoma but with respect to Restronguet Creek, the influence of the point source of contamination is reinforcing the effects of environmental stress. It is generally accepted that pollution reduces diversity and populations (Setty and Nigam, 1984[21]). The Restronguet Creek foraminiferal data shows changes in the standing crops with the population of previously barren stations, temporal and spatial faunal shifts and a general increase in numbers of living organisms.

The abundance of deformed tests decreased at all the stations in Restronguet Creek from the beginning of the study. In particular, the low estuary stations, BY28 and PI30, have values which correspond to the maximum percentage found in the control estuaries. Test deformation occurs naturally within foraminiferal populations (Alve, 1995[4]) but it has been established by the work of Sharifi and others (1991[7]) that exposure to elevated levels of heavy metals results in higher abundance of test deformity. In this investigation, highest abundances occur at stations subject to the highest concentrations of heavy metals, ie. those stations close to the discharge point at Wheal Jane. The abundances of deformed foraminifera in the control estuaries is considered to be high relative to other localities around the world. Almogi-Labin, for example, considers 1% to be the background level of test deformity (pers. comm.,1993). This regional anomolie may exist because of the metalliferous characteristics of the regions geology and weathering thereof, which will produce the elevated background concentrations of heavy metals in south west England estuaries not subjected to prolific mining. The background levels in metals and test deformity will, therefore, be higher in comparison with esturaries draining non-metalliferous geological areas of the U.K.

An acidified habitat can have a dual effect on foraminiferal tests through the dissolution of the tests and remobilisation of sediment bound metals. Dissolution of the tests has statistical implications by the poor preservation of the empty tests. Loss of empty (dead) tests will artificially elevate the living assemblage, producing a bias in the data (Stubbles and others, 1996[22]). During periods of high rainfall in the autumn and winter, Nangiles adit discharges untreated mine water (Figure 5). Specimens from the earlier taken samples in the autumn and winter show the severest effects of dissolution. The area affected by acidic and metal contamination occupied a large area within the Creek but since the spring of 1994 the area of severe effect has been reduced and the intensity of acid attack on the tests has lessened (Figure 10).

Variations in pH are shown to have an important impact on metal mobilisation but this is only significant with respect to Restronguet Creek. The sediment analysis for available metals has shown that some differences occur from year to year but they appear not to have dramatically affected foraminiferal populations. Relative to the control estuaries, however, there is a significant increase in metal concentration and comparisons have shown that the lowest values recorded for Restronguet Creek are greater than the highest readings obtained from the control estuaries. Bryan and Langston (1992[23]) reported that Restronguet Creek is a grossly polluted site in terms of the U.K rivers and estuaries. Our data are in close aggreement with that of Burt and others (1992[24]) and Bryan and Langston (1992[23]), differences in time of sampling, sample location, analytical error, variation in preservtion techniques (Kersten and Forstner, 1987[25]) and the extraction method used (Martin and others, 1987[26]) being sufficient to account for the difference.

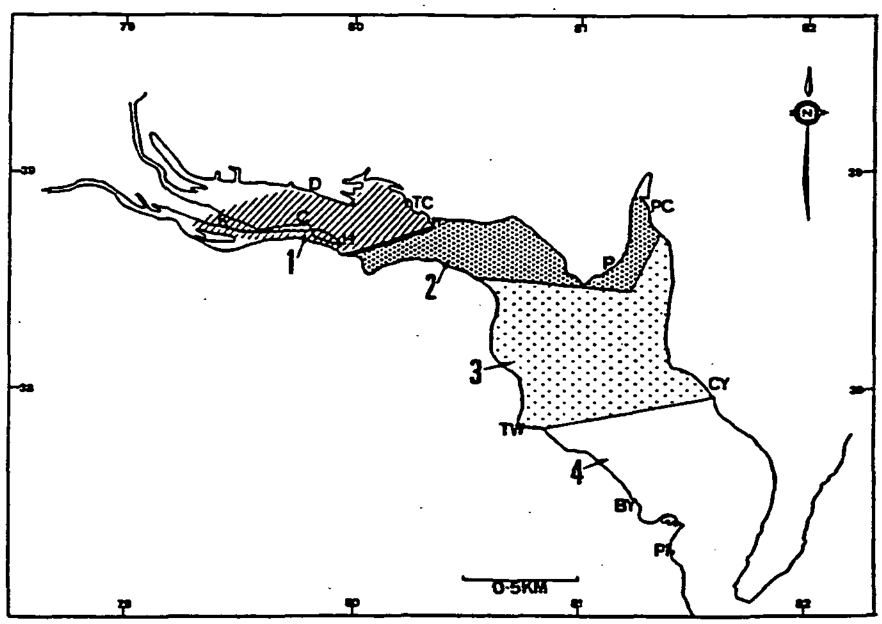


Fig.10. Sub-environments of contamination levels in Restronguet Creek. Zone 1-severely polluted, and zone 2-badly polluted, zonation based on acute acid dissolution and highest abundances of test deformity, zone 3 moderately polluted and zone 4 slightly polluted, zonation based no acid dissolution and lower abundances of test deformity. These zones are now shifted up estuary and zones 1-4 are as follows, badly polluted, moderately polluted, slightly polluted and not polluted.

Conclusions

The changes in foraminiferal distribution and test condition in Restronguet Creek coincide with a decrease in pollution, following 4 years of mine water treatment. Foraminiferal test condition and standing crop abundances appear not to have been affected by the higher metal concentration in the sediment samples taken in 1993 relative to 1992. It may be that the metals were largely unavailable to the organism at a time when pH had increased from 4.4 in 1992 to 6.2 in 1993 and future research will investigate using other extraction methods to determine available metals. It is suggested here, therefore, that foraminifera are influenced by the concentrations of heavy metals in solution and are not greatly affected by sediment bound metals. Periodic mine water discharges, how long the metals remain in the dissolved state (as determined by pH levels) and the remobilistion of sediment bound metals by acidified river water are considered to be the controlling factors influencing foraminiferal response to pollution.

Acknowledgements

The authors wish to thank the technical staff for their assistance. We are also grateful to the following people who gave access across their land, Anthony Mildmay-White (The Flete Estate), St. Winnow Yachts, Dr. and Mrs. Shirer (Tregunwith Wood), Helen Hougth, landlady of the Pandora Inn, Restronguet Creek Boat Repairs, Mr. Holt (Devoran). Sheila Stubbles is especially grateful to the following people; Jane Green and Dr. Roy Moate for help in all aspects of the SEM work, to Dave Griffiths and Tony Smith for their help with diagram scanning and slide production, Roger Bowers and Sarah Hawkins for their assistance with the geochemical analysis, Catherine Fileman, Elaine Drury, Simon Culling and Nathan Mathews(NRA) for supplying the water quality data, Mr. B. Simpson (local historian), The Harold Hyam Wingate Foundation which financially supports this research and finally to her family for their continued support.

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The Ecological and Palaeoecological Implications of the Presence and Absence of Data: Evidence from Benthic Forminifera

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Stubbles, S.J., Green, J.C., Hart, M.B. and Williams, C.L. The ecological and palaeontological implications of the presence and absence of data: evidence from benthic foraminifera. *Proceedings of the Ussher Society*, 9, 054-062

Postmortem modification of foraminiferal assemblages is evident from samples taken during a pollution monitoring programme which uses Recent benthic foraminifera in estuaries in south-west England as biomarkers of heavy metal pollution. The foraminiferal assemblages present in the control estuaries, Fowey and Erme, have undergone postmortem modification by the net addition of empty tests of non-indigenous species. In contrast, a polluted site, Restronguet Creek, suffers a net loss of both indigenous and introduced empty tests (mainly Recent).
There are both man made and natural causes accountable for these postmortem influences. In the case of Restronguet Creek, the net loss is due to acidic drainage emanating from old mine workings, in particular Wheal Jane tin mine. The Restronguet Creek samples have a small non-indigenous species component of c.5%, compared with <1% in samples taken three years ago, indicating that a rise in pH has occurred during that period. The loss of empty indigenous and introduced calcareous tests through acid dissolution artificially elevates the relative live to dead assemblages and the two assemblages resemble each other with respect to diversity. The absence of agglutinated foraminifera in Restronguet Creek reduces diversity further. The Erme estuary naturally accumulates material of marine origin brought in by tidal activity and at any time greater than 30% of the samples (live plus dead) may contain non-indigenous species. The abundance of introduced species can exceed that of the dominant indigenous species. The dead assemblage from the Fowey comprises <10% non-indigenous species. The reason for this low abundance of introduced species may be due to the dredging of the lower estuary area. The order of test accumulation is, Erme >Fowey >Restronguet Creek.
The effects of loss and gain of indigenous and introduced foraminifera have implications with respect to palaeoecological and palaeoenvironmental reconstructions from the fossil record. The loss and gain of specimens will also affect ecological interpretations of Recent data used to assess the effects of pollution.

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Introduction

A programme monitoring heavy metal pollution using Recent benthic foraminifera as biomarkers, has been carried out in selected estuaries in south-west England since June 1992, following a major discharge of drainage water from Wheal Jane tin mine (Cambridge, 1995). It has been established that foraminifera respond to heavy metal pollution in a number of ways, eg. lower standing crops, high abundance of deformed tests, lower diversity, changes in species dominance and test dissolution (Stubbles *et al.*, 1995). The work of Stubbles (1993) outlines the results of the preliminary samples taken from Restronguet Creek in July 1992 (Figure 1). Stubbles *et al.* (1995) described the dual effects of acidic mine drainage on foraminiferal tests by direct structural weakening of the test wall by dissolution and indirectly by the effects of enhanced extracellular and intracellular metal concentration and the consequent effects on cell metabolism. Stubbles *et al.* (1996) reviewed the results obtained during the preceding three years. The distribution of agglutinated foraminifera from the tidal flats and saltmarsh of the Erme (a control estuary) were described by Stubbles (1995).

This paper primarily uses data from Restronguet Creek (Figure 1) and the Erme (Figure 2) intertidal mudflats and saltmarsh, to illustrate the two contrasting phenomena of addition and loss of foraminifera and the implications of postmortem changes. Taphonomy (postmortem alteration of assemblages) is, under certain circumstances, a major influence on foraminiferal assemblages and may be common. Hitherto, research has generally concentrated on the influence of gain by transport (Murray, 1976, 1992b; Wang and Murray, 1983) and the differences between the live, dead and total assemblages (Murray, 1982; Haynes and Dobson, 1969). Kontrovitz *et al.* (1978) modelled the transport potential of 12 benthic species and, although distilled water was used in their experiments rather than seawater which has a higher density, their results show that rates of transport can be species dependant. The species which are introduced into a particular habitat such as the Erme may be derived from a variety of sources, including reworked fossil material and distant living assemblages, but appear as empty tests. However, identifying introduced dead specimens is difficult and often relies on the colour

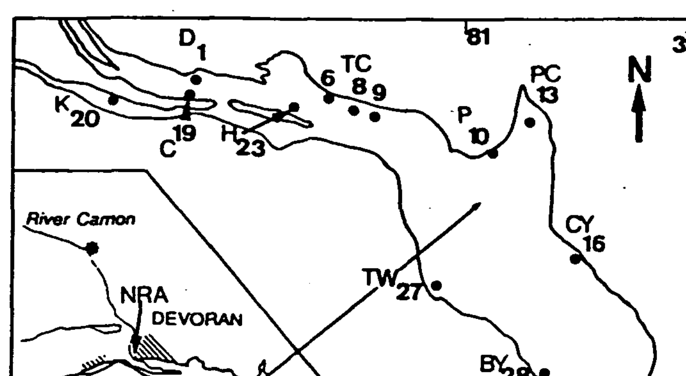


Figure 1. Sketch map of Restronguet Creek showing sample stations. The inset map shows the point of discharge which is denoted by an asterisk and the small arrow indicates the position of the NRA monitoring station.*

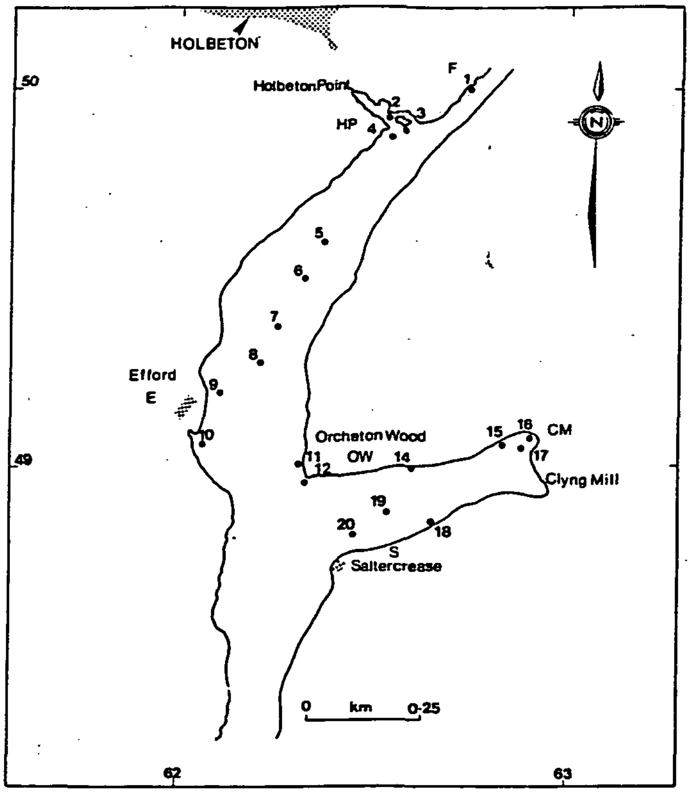


Figure2. Sketch map of The Erme estuary and sample stations.

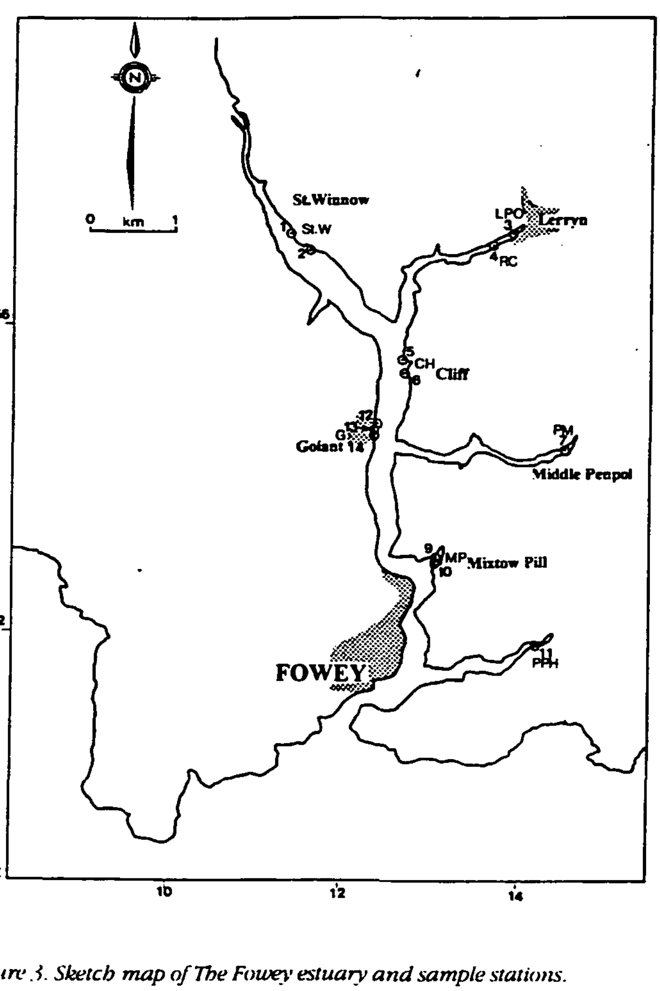


Figure 3. Sketch map of The Fowey estuary and sample stations.

(iron staining) and condition of the test as indicators of age : physical abrasion caused by transport (Murray and Wright, 19

Restronguet Creek, however, has a converse profile, with l of material because of the acidic waters emanating from ab doned metalliferous mines. The acidifed water is derived from redox conditions prevalent in the mine workings and resultant oxidation of suphide minerals producing sulphuric a and metals in solution. This very specific example of taphonor provides a model similar to, but more severe, than that descri by Nagy and Alve (1987) for Sandebukta in Oslo Fjord. The effe of acid dissolution have implications with respect to statisti analyis of the data and their interpretations. It is the aim of present paper to show how pollution monitoring and the effe of pollution are highly dependant upon the use of stain foraminiferal assemblages and the type of data analysis used. also show the importance of separating allochthonous a autochthonous components in palaeoecological reconstructio by providing insights into the effects of gain and loss individuals and species from the habitats under investigtion.

The Environments

The monitoring programme incorporates the systematic, se sonal sampling of the extensive tidal mudflats and saltmarsh present, with the exception of the Fowey (Figure 3), where t saltmarsh lies outside the sample area and the samples we taken from the tidal mudflats only. The locations sampled a

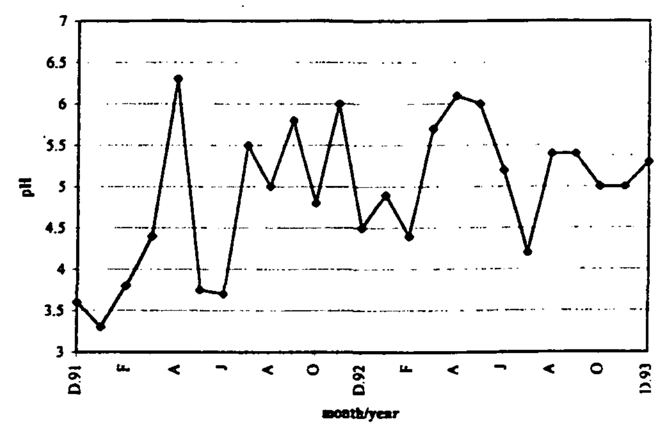


Figure 4. Mean monthly pH (December 1991 to December 1993) record at Devoran Road Bridge monitoring station (Restronguet Creek). Da provided by the NRA.

Figure 5. Mean monthly pH (January 1994 to January 1996) recorded Devoran Road Bridge monitoring station (Restronguet Creek). Data provid by the NRA.

macrotidal rias, where fresh water outflow is low relative to tidal inflow. The Fowey estuary is larger in length, width and depth than that of the Erme, but is also orientated north-south.

Restronguet Creek is orientated north-west - south-east, opening out into the Carrick Roads, the estuary of the Fal. The water and sediment conditions in the Creek are acidic, and at the height of the mine water discharge the pH was c.3.1 at Devoran road bridge monitoring station (National Rivers Authority, 1992). Figures 4 and 5 show the recorded mean monthly water pH values from December 1991 to January 1996. Currently, the water pH is 6.3 at the Devoran monitoring station, but is 8.0 at the mouth of the Creek, just below station PI30. The sediment is slightly acidic, c.pH 6.4-6.7 at the upper estuary stations; D1, C19,TC6, TC8 and TC9. Salinity gradients vary from 0-33‰ (parts per thousand) in the winter and 8-35‰ in the summer (Stubbles, 1993; 1995). At the upper estuary stations, the lowest salinity readings are usually between 0 and 12‰ in the winter and up to 18‰ in the summer. Temperature gradients are also evident, surface temperatures varying from 4°C to 11°C in the winter and from 12°C to 18°C in the summer. As with salinity, temperature is extremely variable and dependant upon the amount of freshwater flow and the development, penetration and rate of decay of the thermocline in the estuaries. This seasonal variation is evident for the three estuaries discussed here.

Pollution is relatively low in the Erme estuary (Langston, 1995, pers.comm.). The Fowey is affected by greater human activity, but this is not considered to have a significant effect on the abundance of foraminiferal test deformity which, as in the Erme, is <3% (Stubbles *et al.*, 1996). The major difference between the Fowey and the other estuaries is the daily dredging of the lower estuary area which maintains the water depth necessary for the china clay port to continue operation. The result of this dredging appears to be beneficial with the scouring away of excessive sediment accumulations and contaminants. Relative to the Erme and Restronguet Creek, the Fowey estuary experiences reduced periods of sediment exposure and drying-out, but the greater water depth may be disrupting the species distribution due to current flow and turbulence.

Methods

The standing crop abundance (number of living foraminifera in a given unit area of 78 cm^{-2}) was estimated using the vital stain rose Bengal and those individuals stained were considered living or only recently dead at the time of collection (Murray, 1992a). The problems associated with the use of rose Bengal have been investigated by Bernhard (1989), who found that this stain overestimated the numbers of living foraminifera, because of the postmortem survival of the cytoplasm. The work she later carried out (Alve and Bernhard, 1995) has since found that rose Bengal is more reliable than ATP when there is a high abundance of empty tests, and when the foraminifera are from shallow water environments, as they found that in these situations, the cytoplasm is of short "persistence". The processing methods used and the rose Bengal staining method have been given in detail by Stubbles (1993; 1995). The 250 µm, 125 µm and 63 µm fractions were each subdivided by volume and were picked to obtain a combined total of between 100-250 stained individuals wherever possible.

The cores were taken during a preliminary survey with a Russian peat borer to a depth of 50 cm. At intervals of 5 cm, a 1cm-thick slice was removed and analysed using the same techniques as for the surface samples. Each segment was picked to give absolute abundance.

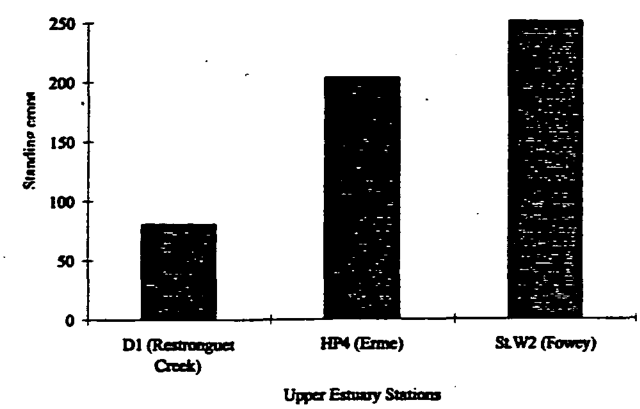
The micrographs (Plate 1) were obtained by mounting several specimens from each foraminiferal species on to a black adhesive circle fixed to an aluminium stub. Each stub was gold coated to a thickness of 8 nm (nano metres) and placed in the Jeol 5200 scanning electron microscope, set to a working distance of 20 mm, at 15 Kv.

The species data are reduced to percentages. Species heterogeneity is determined by The Information Function, H(S) and species richness by the Fisher Index (Fisher *et al.*, 1943). The Information Function provides information on equitability as a function of the eveness of individual species abundance, whereas the Fisher Index is an assessment of species richness and uses all species present, irrespective of abundance (Murray, 1992b).

Results

Standing Crops

Standing crop values vary considerably throughout the estuaries, depending upon elevation, salinity, temperature and season. The standing crops from samples taken from the upper estuary stations of the Erme, Fowey and Restronguet Creek are lower than those for the respective lower estuary stations (Figures 6 and 7). Figure 6 illustrates the spring data for the upper control stations HP4 (Erme) and St.W1 (Fowey) and D1 (Restronguet Creek) and Figure 7 shows the data for the lower estuary stations, with station CY16 having a smaller standing crop than that of the Erme (S19) and Fowey (G14). Comparisons between the control upper estuary stations, HP4 and St.W2 show similar standing crop values, but the values for station D1 (Restronguet Creek) are < 100 per 78 cm^{-2}. The standing crops of the two control lower stations, S19 and G 14 are similar, but there is a marked difference compared with the standing crop data for station CY16. In Restronguet Creek, the upper estuary stations are near the mine water discharge point and stations D1 and C19 were barren until the spring of 1993. It was not until the Summer of 1994 that foraminifera regularly colonised these stations. A small standing crop appeared at K20 in the autumn of 1994 (52)



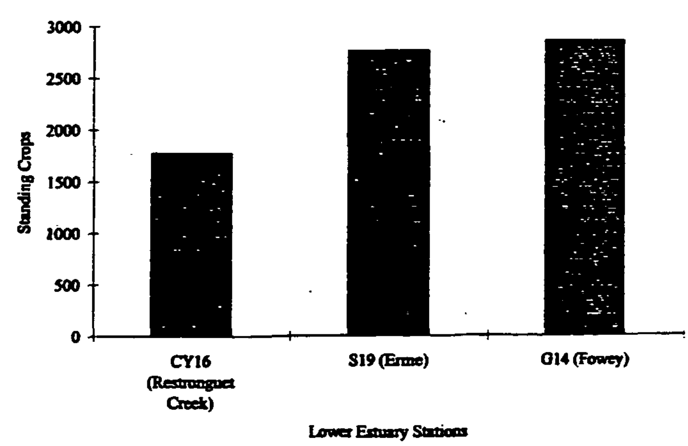


Figure 6. Bar chart showing the variation in spring standing crops (78 cm^{-2}) between the upper stations of the two control estuaries and Restronguet Creek.

Figure 7. Bar chart showing the variation in spring standing crops (78 cm^{-2}) between the lower stations of the two control estuaries and Restronguet Creek.

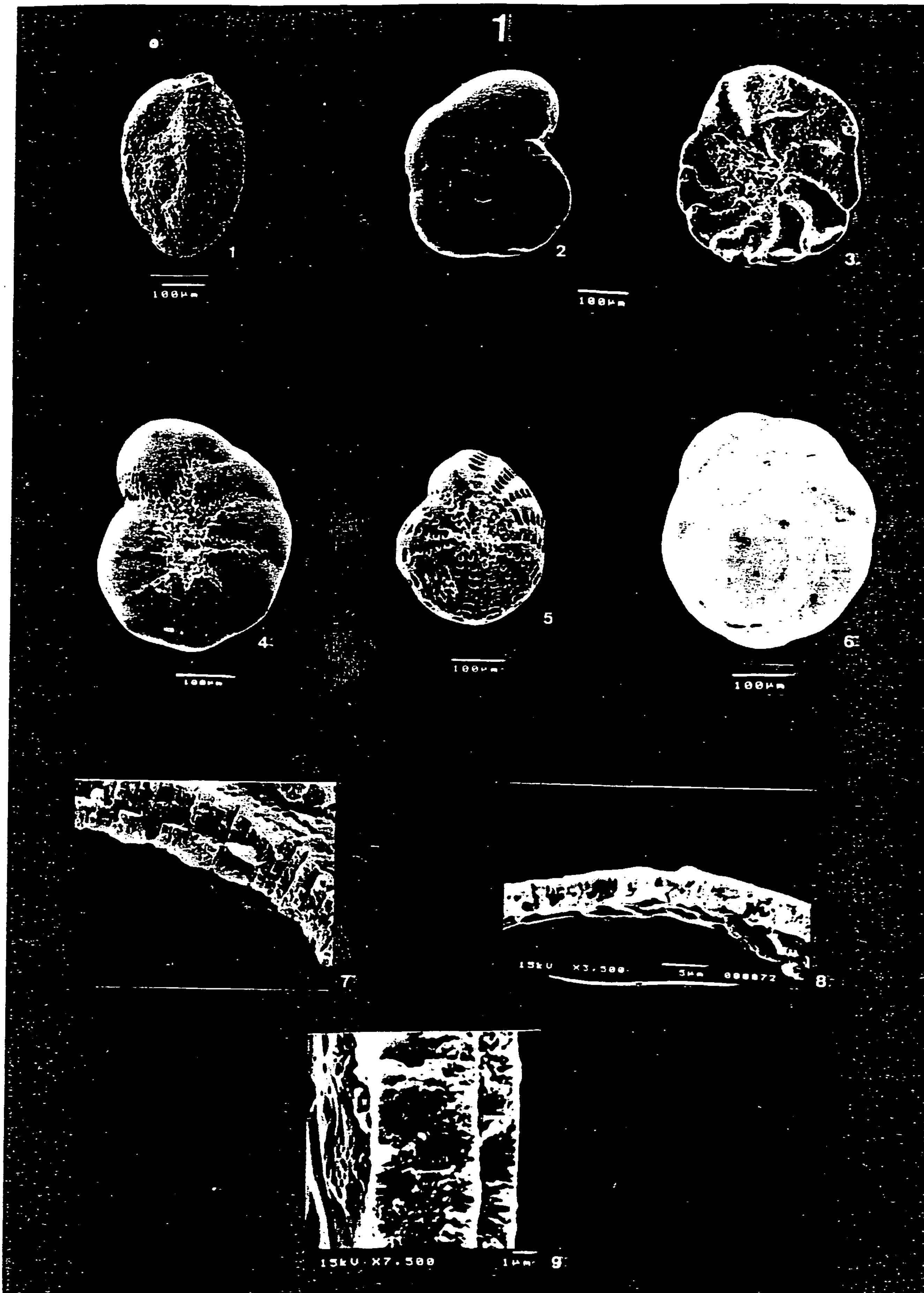


Plate 1. 1. Miliammina fusca. 2. Trochammina inflata. 3. Jadammina macrecsens. 4. Haynesina germanica. 5. Elphidium williamsoni. 6. Amm beccarii. 7. Test wall of a glassy hyaline E. williamsoni showing a clear blocky structure. 8. Test wall of an opaque example of E.williamsoni show poorly defined internal structure and thinner wall. The scale bar is the same as for 7. 9. Test wall of an opaque test showing layering.

and this has remained established. The effects of heavy metal pollution on standing crops persists down estuary in Restronguet Creek, with the low estuary stations, for example, CY16 which has lower standing crops in comparison with the comparable low estuary stations in the control esturies.

Seasonal variations in standing crop are also apparent. The abundance of living individuals at station HP4 (Erme), for example, varies from c. 0-250, and at the low estuary station, S19 from c. 920-2780. The Fowey upper estuary station, St.W2, varies from c.250-1620 and the lower estuary station G14, varies from c.26-2850. Seasonal data for Restronguet Creek (from 1992 - 1995) show the lowest standing crops occur at the stations K20 (c.0-600) and C19 (0-650). The lowest values appear in the winter and the highest in the summer.

The Diversity of Living Assemblages and Species Dominance

A full list of species found in the three estuaries is given by Table 1. The six euryhaline species, *Haynesina germanica, Elphidium williamsoni, Ammonia beccarii, Miliammina fusca, Trochamina inflata and Jadammina macrescens*, are typical of tidal mudflats and saltmarshes and are present in the control estuaries (Plate 1). The Fisher Alpha Index for the living component is <1. Heterogeneity, H(S) is 1.16 for the control locations, but is reduced to 0.9 for Restronguet Creek due to the absence of the three agglutinated species *M.fusca, T.inflata and J.macrescens* (Plate 1).

Species dominance of the living assemblage is seasonally dependent. In the Fowey and Restronguet Creek, the spring and summer are dominated by *H.germanica*, but the winter and autumn are dominated by *E.williamsoni*. The Erme mid to low estuary stations are, in contrast, dominated by *E.williamsoni* throughout the year, with few exceptions (Stubbles, 1995), whilst the upper estuary stations of the Erme are dominated all year by *M.fusca*. This shallow water species is a minor component in the Fowey estuary and only dominates the living assemblage at stations St.W2, LPO3 and RC4 throughout the year. *Ammonia beccarii* is a minor species and rarely appears in the upper estuary live assemblages of any of the estuaries. The standing crops of *A.beccarii* increase down estuary and recently (summer 1995) it was dominant at BY28 (Figure 1).

Test Wall Alteration of Living Calcareous Species

The stained calcareous tests present in the upper areas of Restronguet Creek are opaque, and such tests have been found in samples from stations D1, TC6,8,9, P10, PC13, C19, K20, H23 and to a lesser extent CY16, from the autumn of 1992. Opacity of the test is usually associated with empty tests. Specimens taken from sample stations TW27, BY28 and PI30 have not shown any acid alteration of the test wall and are typically glassy hyaline. Specimens (stained and empty tests) taken from samples in the autumn and winter of 1992/93 from affected stations, showed near catastrophic weakening of the tests. *Haynesina germanica*, in particular, appeared to be unable to strengthen the test by thickening and the tests were preserved only by careful handling (living and dead). In comparison, *E.williamsoni* appeared to be more robust. Since the summer of 1994, the frequency of altered tests and the degree of opacity has decreased with improved water conditions (Stubbles, *et al.*, 1995) and the most affected area has receded towards those stations nearest to the mine water discharge point (D1, C19 and K20), with only occasional occurrences of opaque tests at TC6,8,9, P10, PC13 and H23. The upper estuary stations HP4 (Erme) and St.W1/2 (Fowey) occasionally include examples of opaque calcareous tests (stained), but the tests do not appear to be acutely fragile, thus leading to breaking.

The internal wall appearance of those stained individuals affected by acid dissolution is granular and chalky. It has been found in some stained examples of *E.williamsoni* (Plate 1) that an extra layer has been applied (Stubbles, *et al.*, 1995). Comparison of wall thickness shows the affected specimens to be approximately half the thickness of the hyaline specimens (Plate 1).

The opacity of the tests has meant that the cytoplasm stained with rose Bengal is not visible through the wall and specimens have been wetted to achieve this, otherwise they may be mistaken for empty tests (Murray, 1992b). Wetting the specimens, however, causes the red stain to appear more intense compared with the glassy hyaline examples which do not require wetting.

Postmortem Modification by Dissolution and Relative Abundance

Dissolution of the dead assemblage in Restronguet Creek has been acute at stations D1, TC6,8,9, C19, K20 and to a lesser extent at stations P10, PC13 and H23. Stations CY16, TW27, BY28 and PI30 appear not to have been adversely affected by the removal of empty tests by dissolution. Empty tests were not present in significant numbers or with any regularity at stations D1, C19 and H23 until the summer of 1994 and at K20 from the autumn of 1994. It is not possible to provide quantitative loss data due to the absence of agglutinated foraminifera in Restronguet Creek. Such species can be used as a reference to calculate the loss of calcareous species (Murray, 1992b) and Murray (1992a) found that an 'enrichment in agglutinated tests may take place,' in the event of calcareous test dissolution. The spatial and temporal changes in the proportion of living relative to dead individuals can, however, provide a qualitative insight into the residence times of empty foraminiferal tests. The relative abundance of living individuals at station TC6, for example, was 54% in the Autumn of 1992, with a standing crop of 157, but lower in the spring and summer 1993 when it was 17% and 42 % respectively, with standing crops of 100 and 1540. Station TW27, which is not affected by any significant amount of test dissolution, had a relative abundance of 5% living individuals and a standing crop of 1276 (autumn 1992). This is a lower relative abundance of living foraminifera but higher standing crop than that for TC6.

The relative abundances of living individuals for Fowey are frequently above 25%. At the low estuary station G14, for example, the proportion varies from 6% to 50%, with standing crops of 26 and 2850. The Erme frequently has lower relative abundance of living foraminifera in the order of <15%. The low estuary station S19, for example has varying standing crops of 900 (winter), 1025 (autumn), 2280 (spring) and 2780 (summer), but the relative abundance varied only from 6-8%.

The short cores taken from Restronguet Creek show that with increased depth, fewer foraminiferans are found. At station TC6, for example, below 15 cm depth there were no foraminiferans, but they were present to a depth of 30 cm at stations TC9 and TW27. *Haynesina germanica* was dominant throughout the core lengths at stations TC6, TC9 and TW27 with *E.williamsoni* the next species in abundance. No agglutinated foraminifera were present in the cores.The core taken at station E8 (Erme) provided foraminifera throughout the 50 cm length but again a vertical gradient was evident. The Erme core gave a higher abundance than either TC9 or TW27 and *M.fusca* was frequent throughout. It is evident that dissolution is severe at the upper estuary stations of Restronguet Creek, affecting both the surface and buried assemblages of foraminifera.

Samples taken from Restronguet Creek showed only a few specimens with organic test linings and were generally not common. Specimens with organic test linings were more abundant in the samples taken from the control estuaries, particularly from those taken from the saltmarsh stations of the Erme.

Modification of the Dead Assemblages by Passive Transport

The Erme data shows that the addition of large numbers of non-indigenous species can reach 50% of the dead assemblage. The level to which these individuals are added varies with season (tidal current direction and velocities), the proximity of the

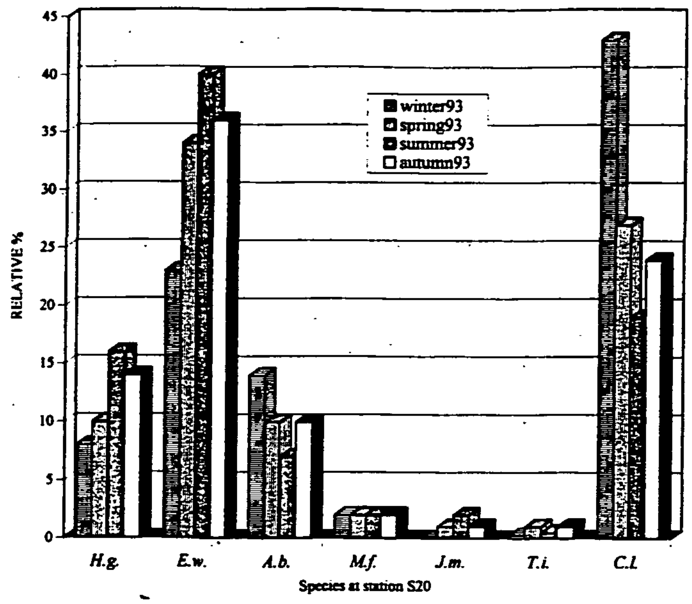


Figure 8. Bar chart showing the proportion of certain species (relative to the total of live and dead species) present at the Erme station S20 for 1993, winter. spring, summer and autumn (including introduced species with a >10% abundance). The abbreviations are as follows, H.g.-H.germanica, E.w.-E.williamsoni, A.b.-A.beccarii, M.f.-M.fusca, J.m-J.macrescens, T.i.-T.inflata and C.l.-C.lobatulus.

sample station to the source of the material and main channel. The upper estuary stations of the three estuaries have a low abundance of introduced foraminifera (<3%), the majority of which appear in the 63μm fraction. The introduced species *Cibicides lobatulus* (Figure 8) has the highest abundance, between 18-43% at station S20 (Erme), but other species not indigenous to the estuary are less than 2% of the dead assemblage and are of low individual abundance (see Table 1). The Fowey, however, has a much reduced allocthonous component, <10% of the dead assemblage, with no individual species exceeding 1%. In contrast, data for Restronguet Creek shows that there is an increasing number of introduced species in the estuary ecosystem. At the outset of sampling those stations nearest to the mouth comprised 1% non-indigenous species, which now has increased to c.5% of the dead assemblage. Of this 5%, *Elphidium macellum* shows the highest abundance. Introduced species are now regularly found in samples taken at the upper estuary stations, with a 1% abundance at D1, where previously none had been found.

It is evident from the estuaries sampled during this programme that a lateral gradient exists, with fewer species being introduced into the upper estuary area and with the highest abundances present nearest to the mouth.

Discussion

The low standing crop values found at the upper estuary stations relative to the lower estuary stations, are coincidental with the variable physical conditions of, for example, salinity and temperature. These are regarded as naturally occurring abiotic environmental stresses (Parker and Athearn, 1959). With respect to Restronguet Creek, however, the foraminifera are also responding to the effects of heavy metal pollution and acidification and this is shown by the comparatively lower standing crops for the Creek (Figures 6 and 7).

Others have found that low pH conditions alone, in the absence of heavy metal pollution, are sufficient to affect foraminiferal distribution and abundance. The low pH conditions and other variable physical conditions, eg. salinity, may account for the patchy foraminiferal distribution noted at stations HP2, HP3 and HP4 of the Erme (Stubbles, 1995). De Rijk (1992) found no calcareous species in the high and upper marsh samples t from the Great Marsh at Barnstable, Massachusetts. This attributed to the low pH conditions prevailing. Schafer (1 concluded that the establishment of calcareous species facilitated by a minimum pH of 6.7 being maintained. The for Restronguet Creek show that *H.germanica* and *E.william* have colonised stations with a minimum water pH of 5.8. A values less than 5.8 no living foraminifera were present at stat D1 and C19 prior to the spring sample of 1993. The experim carried out by Bradshaw (1961) suggest that foraminifera resistant to low pH conditions for relatively short periods of t between 25 and 75 minutes at pH 2.0, but found that *A.becc* was able to recalcify its test following complete dissolut although pseudopodial and feeding activity were slugg Bradshaw (1961) also concluded that resistance to low pH species dependent. It has become apparent from the Restron Creek data that *A.beccarii* is becoming better established dominating the live assemblage at station BY28. This impro ment is coincidental with higher pH and lower concentration heavy metals following long periods of low pH (Figures 4 an and heavy pollution. The effects of acidification on fish populati has been investigated by several workers. Beamish and Har (1972) attributed the loss of fish stocks in the lakes of south-w Sudbury to increasing levels of acidity (<pH 4.5) and found pH values above 5.5 were not lethal but did affect fecund During his investigations on the effects of metals, particularly Cu, Fe, Pb, Zn and Cd, Freda (1991) found that acidity was primary control on fish reproduction; below the pH of ac ponds (<pH 3.8) fish fecundity was severly affected. The intir relationship between pH and heavy metal behaviour which le to changes in toxicity, elevated concentrations of heavy meta solution, as well as the reactivation of sediment bound me (Stubbles, *et al.*, 1995) has also been investigated by Freda (19 Freda found that the solubilities of Cu, Zn and Cd were high the pH range of 4.0 - 7.0, but for Al the range was pH 4.0 - Wren and Stephenson, 1991 also found that metal behav depended upon the metal and pH range, and that Cd was toxic to freshwater invertibrates below pH 5.5. Uptake of Cd increased in the range of pH 7.0 - 5.5, a pH range frequently fo in freshwater.

It is evident from the data that the foraminifera in the up stations in all estuaries experience high levels of environme stress relative to the lower estuary stations and consequently foraminiferal assemblages in the upper estuary stations decre in both diversity and standing crop values (Stubbles, 1995), only the euryhaline species thriving under low salinity co tions. De Rijk (1995) concluded that salinity is independen elevation, but that certain species were indicative of low salin Low diversity is a significant feature of the intertidal area estuaries, with a limited number of indigenous species tolera the variable conditions. Low diversity is also indicative pollution (Murray, 1992a; 1992b, Alve, 1995 and Stubbles, 19 and the absence of the agglutinated foraminifera in Restron Creek is probably due to the high concentrations of heavy me particularly in the high estuary area. The higher stations in control estuaries are dominated by *M.fusca*.

Predation can also influence the abundance of foramini (Moodley *et al.*, 1993). However, in Restronguet Creek, wl has a low species diversity and low abundance of macro micro benthos (Bryan and Hummerstone, 1971), predation is considered to be a major factor in foraminiferal survival and the standing crop abundance. However, predation is likel affect the foraminiferal assemblages of the Erme and Fo estuaries where predators are more abundant.

The diversity of the dead assemblages from the co estuaries is higher than that of the living assemblage. The d assemblage is the combined total of empty indigenous tests those introduced, and each of these components will repre several generations. The degree to which this allochthor component dominates the dead assemblage depends upon conditions prevalent for each individual estuary, but it is co ered that overall, the dead assemblage will outnumber the li

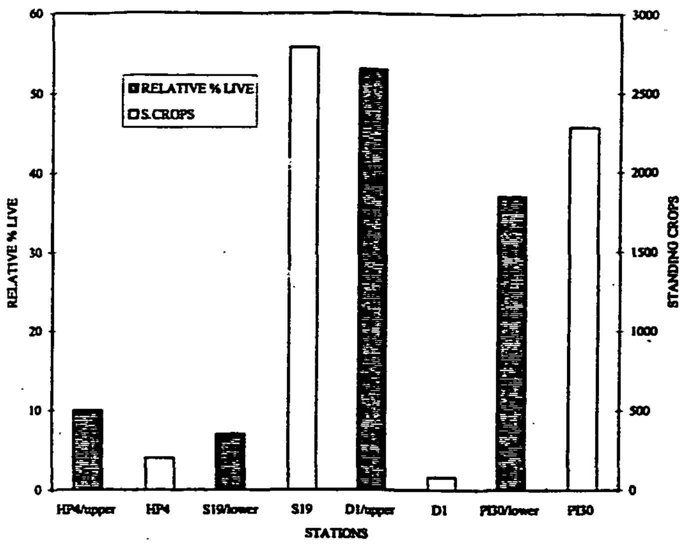


Figure 9. Bar chart showing the different information gained by using the relative % of living and the standing crop methods. The upper estuary stations HP4 and D1 and the lower estuary stations S19 and PI30 are used in the analysis.

and, for the diversity, the two assemblages of living and dead will regularly be dissimilar (Murray, 1970; 1982; 1992b).

The living assemblage of the Erme gives an alpha value of <1 and H(S) 1.16 from the six indigenous species present throughout the estuary, values expected for an intertidal marsh environment (Murray, 1992b). The dead assemblage at stations in the lower Erme estuary, however, gave high alpha indices of 8 and H(S) 2.13. With respect to the Erme data there is, therefore, a notable difference between the dead and living assemblages and they do not resemble each other. Smart and Murray (1995) concluded that the diversity of a local population will be "ephemeral and prone to migrations in and out of the ecosystem." Consequently samples taken at a particular time can only reflect the species profile for that time and Figure 8 shows that there is seasonal variation in the abundance of introduced species.There are potentialy >70 species introduced (Table 1), which enhances species richness diversity but are generally of low individual abundance, with the exception of *C. lobatulus* (Figure 8). The habitat of this species may be a contributory factor accounting for its high relative abundance as it is epifaunal and can easily be detached after death and then transported. The high abundance of *C.lobatulus* in the Erme effectively displaces the dominant indigenous species *E.williamsoni* in the winter. Furthermore, *C. lobatulus* is of greater abundance throughout the year relative to the minor indigenous species, for example, *T. inflata* and *J. macrescens*, and *M.fusca* which at the low estuary stations is also a minor species (Stubbles, 1995). In the absence of staining, living and dead individuals cannot be differentiated and working with only total assemblages would indicate that the low estuary data were obtained from more saline (marine) situations. Removal of species with less than 5% abundance of the dead assemblage from the analysis simplifys the profile, but such adjustment requires care due to the low abundance of the indigenous species *M.fusca, T. inflata* and *J. macrescens* at the low estuary stations (Figure 8). Such examples showing a strong dissimilarity between live and dead assemblages may lead to erroneous interpretations with respect to environmental reconstructions, biofacies determinations and faunal shifts due to catastrophic events if unstained material is used (Patterson, 1990; Williams, 1995). Kontrovitz *et al.* (1978), have shown that the reconstruction of palaeoenvironmental information is affected by the abundance of introduced species which must be separated from the indigenous assemblages. So despite the problems associated with the use of stains (Barnhard, 1989 ; Douglas, *et al.*, 1980), differentiation between the living and dead assemblages is essential, as the differences between the two may be important (Murray, 1970).

It is, therefore, the *similarity* in diversity, between the dead and live assemblages (or absence of fossil foraminifera) in the Restronguet Creek example, that is indicative of high rates of loss. Restronguet Creek shows the least degree of allochthonous influence, perhaps due to the loss of introduced species by acid dissolution. The low pH appears to cause rapid dissolution of the foraminifera after death, in particular removing the non-thickened tests of the introduced species. The work of Boltovoskoy and Totah (1992) has shown that rates of dissolution are species dependent and a preservation index for certain species was defined from their time exposure method in solutions at pH 6.7. The work of Krumbein and Garrels (1952) showed that if pH fell below 7.8, dissolution of calcareous species took place and the experiments of Alve and Murray (1994; 1995) established that a weak acid attack (pH 3.0) will eliminate empty calcareous tests with ease. The pH values, therefore, need not be significantly lower than neutral, as shown by the Restronguet Creek data and the work of others, for rapid dissolution of empty tests to take place. It is also significant that there is a low abundance of organic linings in the Restronguet Creek surface and core samples, which suggests that the residence time of empty tests is short and there are short periods in the intermediate stages of dissolution.

There are at least three possibilities which may account for the absence of foraminifera below 15 cm at station TC6. They are 1. Increasing dissolution with increasing depth of burial; 2. Extensive periods with no foraminiferal production; 3. A combination of 1 and 2. The gradient which exists in all the cores would suggest that dissolution does occur with increased depth, but that the abrupt cessation of individuals at station TC6 below 15 cm can be accounted for by either of the options given above. The absence of agglutinated foraminifera in the Restronguet Creek cores would suggest that this is not a recent phenomenon, but has persisted through the active mining period of the modern Wheal Jane tin mine (1971-1991).

The absence of agglutinated foraminifera and the dissolution of empty calcareous species in Restronguet Creek has implications in any analysis of the data, as will the acquisition of introduced species by non-polluted estuaries. The effects of gain and loss are shown by Figure 9, which compares the standing crop values for Erme stations HP4, S19, and Restronguet Creek stations D1 and P130, with the relative proportion (%) living organisms for the same stations. Those stations, for example, D1 nearest to the discharge point in Restronguet Creek and the more elevated station (HP4) of the Erme (where the accumulation of introduced tests is less and some dissolution may take place), show there to be an enrichment in living relative to dead organisms. For the low estuary stations, S19 and PI30 there is an enrichment of empty tests relative to living foraminifera, thus showing a reduction in the proportion of living individuals at these stations relative to the upper estuary stations. In comparison, however, the standing crops show there to be a converse situation with low standing crops at the high estuary stations and higher standing crops at the low estuary stations.

The relative abundance of living foraminifera at station S19 (Erme), shows little seasonal variation of between 6-8%, but the standing crops vary according to seasonal blooms. This suggests that the gain of empty tests, both indigenous and introduced species, is affecting the relative abundance of living. Consequently, relative abundance of living does not reflect the seasonal blooms of the indigenous species. The Fowey station G14 does, however, show that with low gain of introduced species (through dredging) and little loss (through dissolution) of indigenous empty tests the relative abundance of living does reflect the seasonal variation in standing crops. At station TC6 (Restronguet Creek) there is a decrease in relative abundance of living foraminifera with an increase in standing crops and this does suggest that the dead assemblage is increasing in size.

Conclusions

The changes in the standing crops and increase in the relative abundance of dead vs. living foraminifera from Restronguet

Creek suggest that the surface sample data is influenced by variations in the size of the living and dead assemblages, due to both increasing production and improved natural preservation due to higher pH. With increased productivity and higher pH conditions, more empty tests are being accumulated in the dead assemblage.

Thus the use of the live:dead, live:total ratios, or the relative abundance of living foraminifera is not considered valid for the purposes of this research, which relies on in-situ biomarkers of heavy metal pollution and acidic drainage. The relative abundance of living organisms does not identify foraminiferal responses to natural stress or heavy metal pollution if postmortem influences are high, and this is evident from comparisons made between the relative abundance of living organisms and the standing crop estimates. The latter provides a more reliable insight into foraminiferal distribution and abundance clearly showing the variations that exist within an estuary and reliably identifying areas of stress.

Acid alteration of calcareous tests is readily visible and specimens showing damage and opacity should be regarded as indicative of dissolution potential. It is concluded that care must be taken when using ratios or relative abundance analysis of living assemblages in ecotoxicological research, as the analysis may be affected by postmortem processes, especially if there is evidence of test dissolution or accumulation.

The two converse situations illustrated here show how modern analogues can prove to be useful tools in palaeoenvironmental and palaeoecological reconstruction of fossil assemblages, separating the non-indigenous component from the indigenous. Conversely, net loss of solely calcareous indigenous individuals will result in the absence of a fossil record. The presence or absence of fossil assemblages can be a reflection of unusual events, not otherwise documented by the geological information. In addition, preservation is species dependent. Those species present in a fossil assemblage will be there via various mechanisms. Modern analogues provide some insight into the mechanisms which alter indigenous assemblages but the whole problem of mapping and modelling these postmortem processes is extremely complicated and should be investigated further.

ACKNOWLEDGEMENTS

We are grateful for the assistance given to us by the technical staff in the Department of Geological Sciences and to Dr. C. W. Smart for correcting the first draft of this manuscript. We acknowledge valuable discussions with Professor John Murray during the preparation of this manuscript and the helpful and encouraging comments made by another referee. The opportunity for S. Stubbles to carry out this research has only been made possible by the good patience shown by her family and a scholarship from The Harold Hyam Wingate Foundation. Her thanks go to the following people who kindly gave her permision to access their land; Mr. A.J.B.Mildmay-White of The Flete Estate, F.Stevens and S.Chapman (St.Winnow Yachts), Helen Hough (and her late husband, Roger), landlady of The Pandora Inn, Dr and Mrs. Shirer (Tregunwith House), and The National Trust (Pont Pill).

Table 1 Faunal list of Foraminifera

Indigenous species

Ammonia beccarii (Linné) 1858
Elphidium williamsoni Haynes 1973
Haynesina germanica (Ehrenburg) 1840
Jadammina macrescens (Brady) 1870
Miliammina fusca (Brady) 1870
Trochammina inflata (Montague) 1808

Non - indigenous species

Amphicoryna cf. A. scalaris (Batsch) 1791
Astacolus crepidulus (Fichtel and Moll) 1798
Asterigerinata mamilla (Williamson) 1858
Bolivina pseudoplicata Heron-Allen and Earland 1930
Brizalina cf. B. pseudopunctata (Höglund) 1947
Brizalina spathulata (Williamson) 1858
Brizalina variabilis (Williamson) 1858
Buccella frigida (Cushman) 1921
Bulimina elegantissima d'Orbigny 1846
Bulimina gibba Farnasini 1920
Bulimina marginata d'Orbigny 1826
Cancris auricula (Fichtel and Moll) 1798
Cassidulina obtusa Williamson 1858
Cibicides lobatulus (Walker and Jacob) 1798
Cornuspira foliacea (Philippi) 1844
Cyclogyra involvens (Reuss) 1850
Eggerella scabra (Williamson) 1858
Elphidium crispum (Linné) 1758
Elphidium gerthi Van Voorthuysen 1957
Elphidium macellum (Fitchel and Moll) 1798
Elphidium margaritaceum (Cushman) 1930
Fissurina lagenoides (Williamson) 1848
Fissurina lucida (Williamso) 1848
Fissurina marginata (Montagu) 1803
Fissurina orbignyana Seguenza 1862
Fursenkoina fusiformis (Williamson) 1858
Glabratella milletti (Wright) 1911
Gavelinopsis praegeri (Heron-Allen and Earland) 1913
Glandulina ovula d'Orbigny 1846
Globigerina bulloides d'Orbigny 1826
Globulina gibba d'Orbigny 1826
Globulina d'Orbignyi var. myristiformis (Williamson) 1858
Globocassidulina aff. G. *subglobosa* (Brady) 1881
Guttulina lactea (Walker and Jacob) 1858
Guttulina lactea var. *concava* (Williason) 1858
Haplophragmoides wilberti Anderson 1953
Lagena clavata (d'Orbigny) 1846
Lagena interrupta Williason 1848
Lagena laevis (Montagu) 1803
Lagena perclucida (Montagu) 1803
Lagena semistriata Williamson 1848
Lagena substriata Williamson 1848
Lagena sulcata (Walker and Jacob) 1798
Lagena tenuis (Bornemann) 1855
Lamarckina haliotidea Heron-Allen and Earland
Lenticulina peregrina (Schwager) 1866
Lenticulina sp.
Massilina secans (d'Orbigny) 1826
Nonian depressulus (Walker and Jacob) 1798
Nonionella turgida (Williamson) 1858
Oolina hexagona (Williamson) 1858
Oolina lineata (Williamson) 1858
Oolina melo d'Orbigny 1839
Oolina squamosa (Montagu) 1803
Oolina williamsoni (Alcock) 1865
Orbulina universa d'Orbigny 1839
Parafissurina malcomsoni (Wright) 1911
Patellina corrugata Ehrenberg 1843
Pateoris hauerinoides (Rhumbler) 1936
Procerolagena gracilis (Williamson) 1848
Prygo depressa (d'Orbigny) 1826
Quinqueloculina bicornis (Walker and Jacob) var. angulata (Williamson) 1
Quinqueloculina dimidiata Terquem 1876
Quinqueloculina lata Trequem 1876
Quinqueloculina oblonga (Montagu) 1803
Quinqueloculina semimulum (Linné) 1758
Reophax moniliformis Siddall 1886
Rosalina anomola Terquem 1875
Rosalina willamsoni (Chapman and Parr) 1958
Sprillina vivipara Ehrenberg 1843
Spiroloculina excavata d'Orbigny 1846
Trochammina ochracea (Williamson) 1858
Trochammina rotaliformis Heron-Allen and Earland 1911

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