THE ECOLOGICAL AND PALAEOECOLOGICAL IMPLICATIONS OF THE PRESENCE AND ABSENCE OF DATA: EVIDENCE FROM BENTHIC FORMINIFERA

S.J. STUBBIES, J.C. GREEN, M.B. HART AND C.L. WILLIAMS

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.

S.J. Stubbles, M.B. Hart and C.L. Williams, Department of Geological Sciences,
The University of Plymouth, Drake Circus, Plymouth, Devon, PL1 8AA
J.C. Green, Plymouth Marine Laboratory, Citadel Hill, Plymouth, Devon, PL1 2PB

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 (iron staining) and condition of

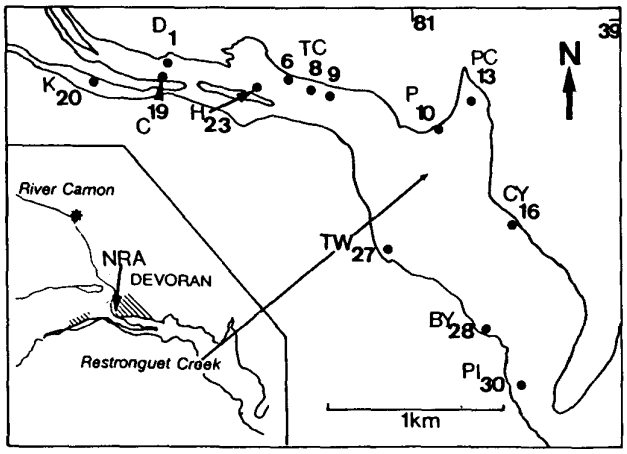


Figure 1. Sketch map of Restronguet Creek showing sample stations. The inset map shows the point of discharge which is denoted by an asterisk and the small arrow indicates the position of the NRA monitoring station.*

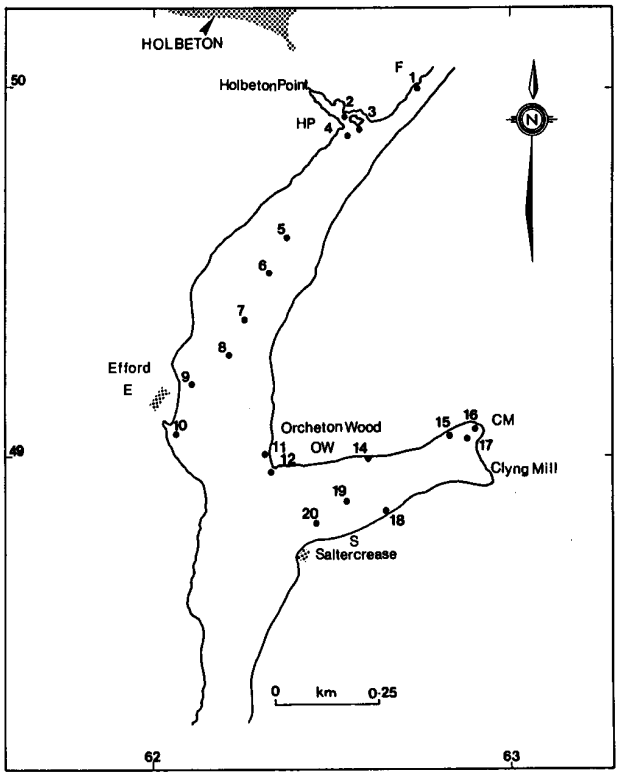


Figure 2. Sketch map of The Erme estuary and sample stations.

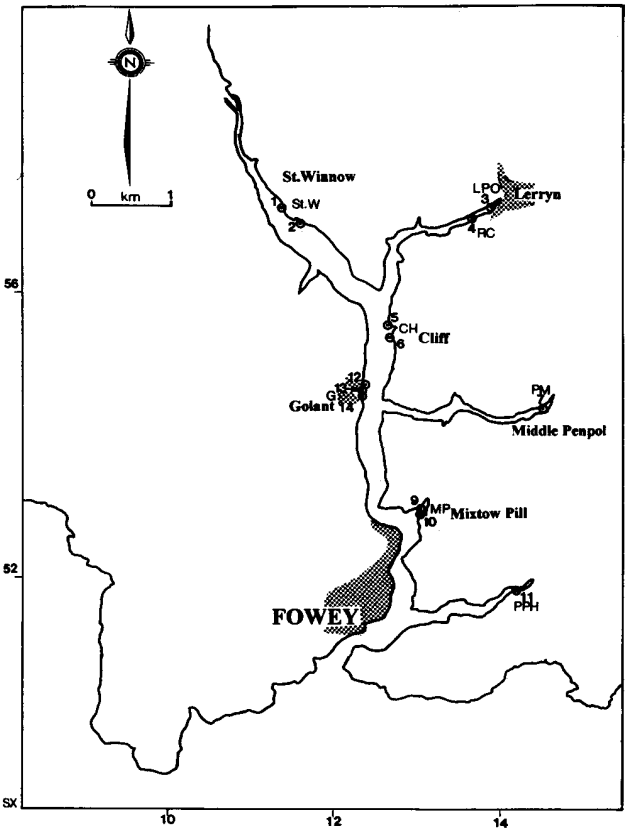


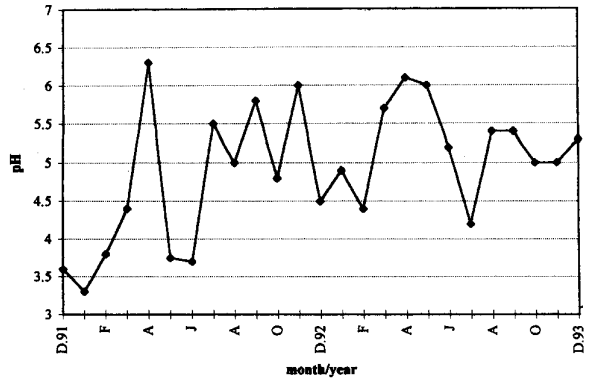
Figure 3. Sketch map of The Fowey estuary and sample stations

the test as indicators of age and physical abrasion caused by transport (Murray and Wright, 1970).

Restronguet Creek, however, has a converse profile, with loss of material because of the acidic waters emanating from abandoned metalliferous mines. The acidified water is derived from the redox conditions prevalent in the mine workings and the resultant oxidation of suphide minerals producing sulphuric acid and metals in solution. This very specific example of taphonomy, provides a model similar to, but more severe, than that described by Nagy and Alve (1987) for Sandebukta in Oslo Fjord. The effects of acid dissolution have implications with respect to statistical analysis of the data and their interpretations. It is the aim of the present paper to show how pollution monitoring and the effects of pollution are highly dependant upon the use of stained foraminiferal assemblages and the type of data analysis used. We also show the importance of separating allochthonous and autochthonous components in palaeoecological reconstructions, by providing insights into the effects of gain and loss of individuals and species from the habitats under investigation.

The Environments

The monitoring programme incorporates the systematic, seasonal sampling of the extensive tidal mudflats and saltmarshes present, with the exception of the Fowey (Figure 3), where the saltmarsh lies outside the sample area and the samples were taken from the tidal mudflats only. The locations sampled are macrotidal rias, where fresh



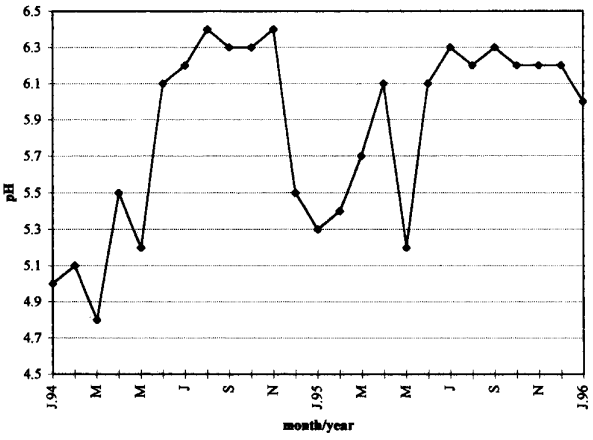


Figure 4. Mean monthly pH (December 1991 to December 1993) recorded at Devoran Road Bridge monitoring station (Restronguet Creek). Data provided by the NRA.

Figure 5. Mean monthly pH (January 1994 to, January 1996) recorded at Devoran Road Bridge monitoring station (Restronguet Creek). Data provided by the NRA.

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 P130. 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 (Aloe 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 pm, 125 pm and 63 pm 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 Dl (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 Dl 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) and this has remained

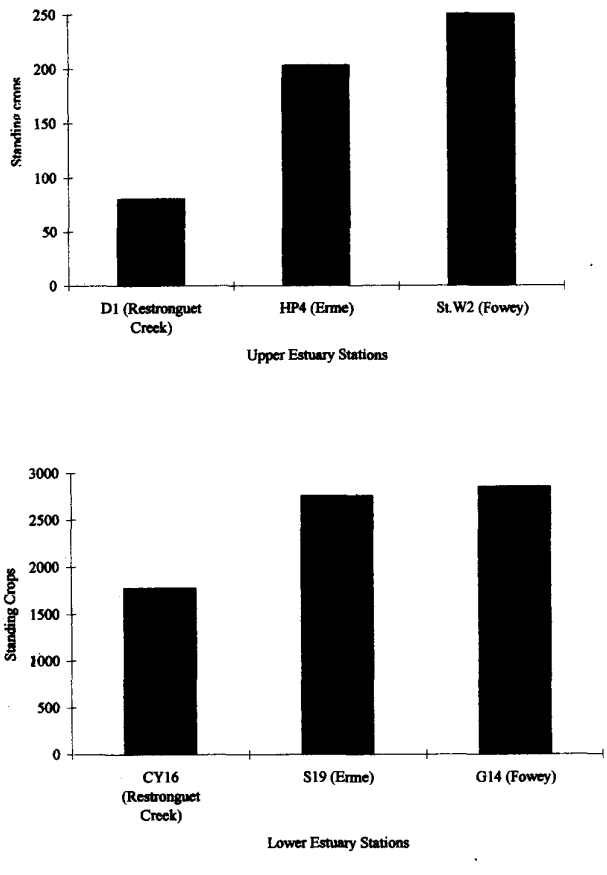


Figure 6. Bar chart showing the variation in spring standing crops (78 cm^{-2}) between the upper stations of the two control estuaries and Restronguet Creek.

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.

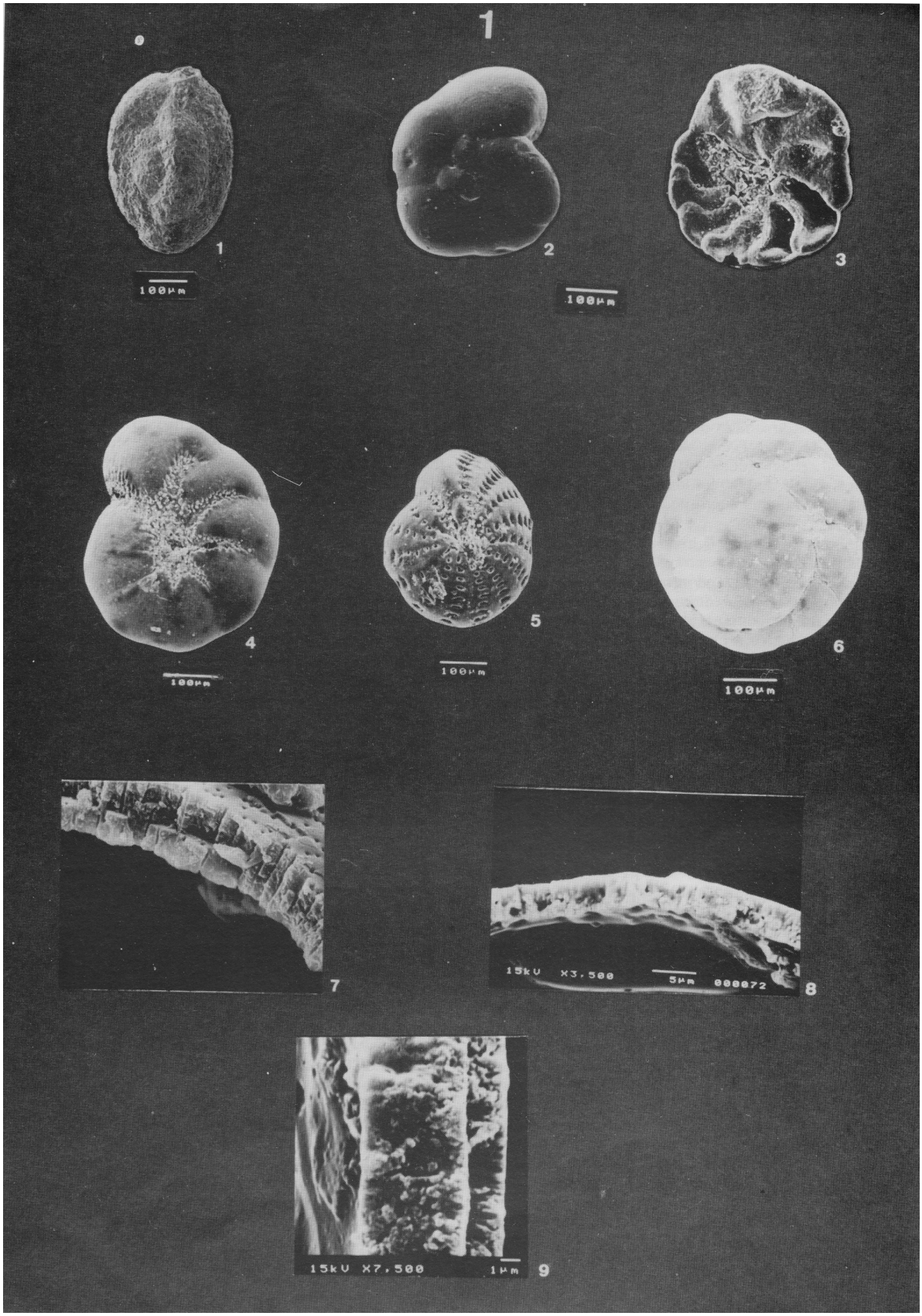


Plate 1. 1. Miliammina fusca. 2. Trochammina inflates. 3. Jadammina macrecsens. 4. Haynesina germanica. 5. Elphidium williamsoni. 6. Ammonia beccarii. 7. Test wall of a glassy hyaline E. williamsoni showing a clear blocky structure. 8. Test wall of an opaque example of E.williamsoni showing a poorly defined internal structure and thinner wall. The scale bar is the same as for 7. 9. Test wall of an opaque test showing layering.

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.0600) 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 Dl, 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 P130 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 (Dl, 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 Dl, TC6, 8, 9, C19, K20 and to a lesser extent at stations P10, PC13 and H23. Stations CY16, TW27, BY28 and P130 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 Dl, 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 sample station to the

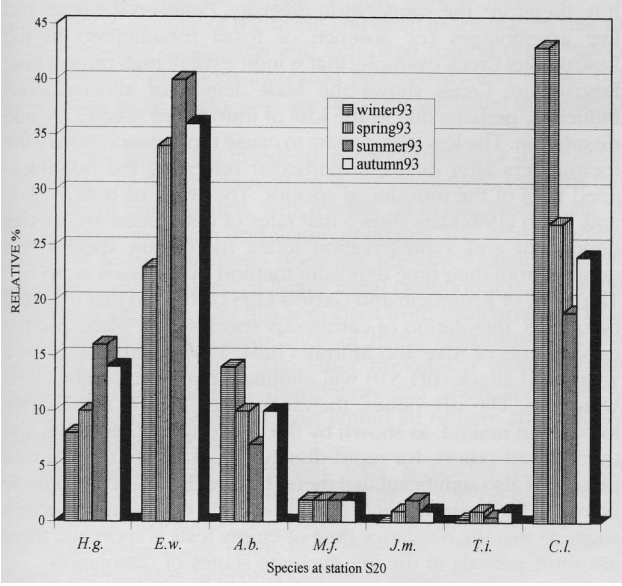


Figure 8. Bar chart showing the proportion of certain species (relative to the total of live and dead species) present at the Erme station S20 for 1993, winter, spring, summer and autumn (including introduced species with a >10% abundance). The abbreviations are as follows, H.g.-H.germanica, E.w.-E.williamsoni, A.b.-A.beccarii, M f-M.fusca, J.m-J.macrescens, Ti.- T.inflata and C.l.-C.lobatulus.

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 63pm 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 taken from the Great Marsh at Barnstable, Massachusetts. This was attributed to the low pH conditions prevailing. Schafer (1970) concluded that the establishment of calcareous species was facilitated by a minimum pH of 6.7 being maintained. The data for Restronguet Creek show that *H.germanica* and *E.williamsoni* have colonised stations with a minimum water pH of 5.8. At pH values less than 5.8 no living foraminifera were present at stations D1 and C19 prior to the spring sample of 1993. The experiments carried out by Bradshaw (1961) suggest that foraminifera are resistant to low pH conditions for relatively short periods of time, between 25 and 75 minutes at pH 2.0, but found that *A.beccarii* was able to recalcify its test following complete dissolution, although pseudopodial and feeding activity were sluggish. Bradshaw (1961) also concluded that resistance to low pH was species dependent. It has become apparent from the Restronguet Creek data that *A.beccarii* is becoming better established and dominating the live assemblage at station BY28. This improvement is coincidental with higher pH and lower concentrations of heavy metals following long periods of low pH (Figures 4 and 5) and heavy pollution.The effects of acidification on fish populations has been investigated by several workers. Beamish and Harvey (1972) attributed the loss of fish stocks in the lakes of south-west Sudbury to increasing levels of acidity (<pH 4.5) and found that pH values above 5.5 were not lethal but did affect fecundity. During his investigations on the effects of metals, particularly Al, Cu, Fe, Pb, Zn and Cd, Freda (1991) found that acidity was the primary control on fish reproduction; below the pH of acidic ponds (<pH 3.8) fish fecundity was severely affected. The intimate relationship between pH and heavy metal behaviour which leads to changes in toxicity, elevated concentrations of heavy metals in solution, as well as the reactivation of sediment bound metals (Stubbles, *et al.,* 1995) has also been investigated by Freda (1991). Freda found that the solubilities of Cu, Zn and Cd were high over the pH range of 4.0 - 7.0, but for Al the range was pH 4.0 - 5.0. Wren and Stephenson, 1991 also found that metal behaviour depended upon the metal and pH range, and that Cd was less toxic to freshwater invertibrates below pH 5.5. Uptake of Cd was increased in the range of pH 7.0 - 5.5, a pH range frequently found in freshwater.

It is evident from the data that the foraminifera in the upper stations in all estuaries experience high levels of environmental stress relative to the lower estuary stations and consequently the foraminiferal assemblages in the upper estuary stations decrease in both diversity and standing crop values (Stubbles, 1995), with only the euryhaline species thriving under low salinity conditions. De Rijk (1995) concluded that salinity is independent of elevation, but that certain species were indicative of low salinity. Low diversity is a significant feature of the intertidal areas of estuaries, with a limited number of indigenous species tolerating the variable conditions. Low diversity is also indicative of pollution (Murray, 1992a; 1992b, Alve, 1995 and Stubbles, 1995) and the absence of the agglutinated foraminifera in Restronguet Creek is probably due to the high concentrations of heavy metals, particularly in the high estuary area. The higher stations in the control estuaries are dominated by *M.fusca.*

Predation can also influence the abundance of foraminifera (Moodley *et al.,* 1993). However, in Restronguet Creek, which has a low species diversity and low abundance of macro and micro benthos (Bryan and Hummerstone, 1971), predation is not considered to be a major factor in foraminiferal survival and on the standing crop abundance. However, predation is likely to affect the foraminiferal assemblages of the Erme and Fowey estuaries where predators are more abundant.

The diversity of the dead assemblages from the control estuaries is higher than that of the living assemblage. The dead assemblage is the combined total of empty indigenous tests and those introduced, and each of these components will represent several generations. The degree to which this allochthonous component dominates the dead assemblage depends upon the conditions prevalent for each individual estuary, but it is considered that overall, the dead assemblage will outnumber the living and, for the diversity, the two assemblages of

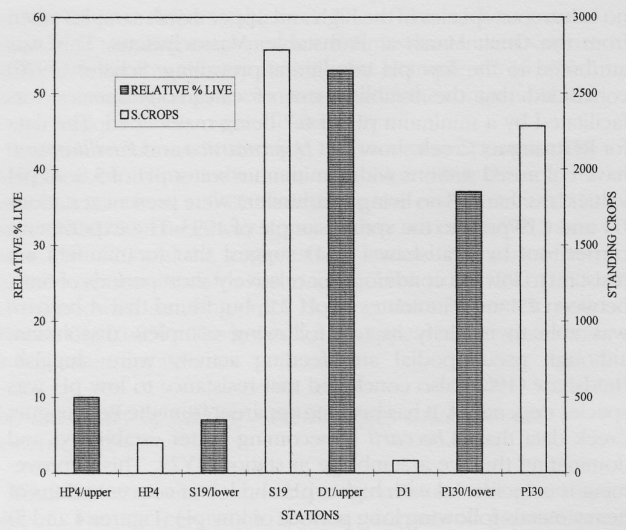


Figure 9. Bar chart showing the different information gained by using the relative % of living and the standing crop methods. The upper estuary stations HP4 and D1 and the lower estuary stations S19 and PI30 are used in the analysis.

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 foraminfera) 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, Dl 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 P130 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

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. Modem 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 permission 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 williamsoniHaynes 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
Comuspira foliacea (Philippi) 1844
Cyclogyra involvens (Reuss) 1850
Eggerella scabra (Williamson) 1858
Elphidium crispum (Linné* 1758
Elphidium gerthiVan 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 (Bomemann) 1855
Lamarckina hallotidea 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 hexagon (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 bloomis (Walker and Jacob) var. angulata (Williamson) 1858 *Quinqueloculina dimidiataTerquem* 1876
Quinqueloculina Iata 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

REFERENCES

ALVE, E. 1995. Benthic Foraminiferal Responses to Estuarine Pollution: A Review. *Journal of Foraminiferal Research,* **25,** no.3, pp.190-203.

AWE, E. and BERNHARD, J.M. 1995. Vertical Migratory Response of Benthic Foraminifera to Controlled Oxygen Concentrations in an Experimental Mesocosm. *Marine Ecology Progress Series,* **116,** pp.137-151.

ALVE, E and MURRAY, J.W. 1994. Ecology and Taphonomy of Benthic Foraminfera in a Temperate Mesotidal Inlet. *Journal of Foraminiferal Research,* **24,** no. 1, pp.18-27.

ALVE, E. and MURRAY, J.W. 1995. Experiments to Determine the Origin and Palaeoenvironmental Significance of Agglutinated Foraminiferal Assemblages. In: *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera.* Eds: M.A. Kaminski, S. Geroch, and M.A. Gasinski. Grzybowski Foundation Special Publication no. **3,** pp.1-11.

BEAMISH, R.J. and HARVEY, H.H. 1972. Acidification of the La Cloche Mountains Lakes, Ontario and Resulting Fish Mortalities. *Journal of Fisheries Research Board of Canada,* **29**, no. 8, pp.1131-1143.

BERNHARD, J.M. 1989. The Distribution of Benthic Foraminifera with Respect to Oxygen Concentration and Organic Carbon Levels in Shallow-water Antarctic Sediments. *Limnology Oceanography,* **34,** no.6, pp.1131-1141.

BOLTOVOSKOY, E. and TOTAH, V.I. 1992. Preservation Index and Preservation Potential of Some Foraminiferal species. *Journal of Foraminiferal Research,* **22,** no.3, pp.267-273.

BRADSHAW, J.S. 1961. Laboratory Experiments on the Ecology of Foraminifera. *Contributions from the Cushman Foundation for Foraminiferal Research,* **XII**, no.3, pp.87-106.

BRYAN, G.W. and HUMMERSTONE, L.G. 1971. Adaptation of the Polychaete *Nerus diversicolor* to Estuarine Sediments Containing High Concentrations of Heavy Metals I. General Observations and Adaptations to Copper. *Journal of The Marine Biological Association,* **51,** pp.845-863.

CAMBRIDGE, M. 1995.Use of Passive Systems for the Treatment and Remediation of Mine Outflows and Seepages. *Minerals Industry International* pp.35-42.

DeRIJK, S. 1995. Salinity Control on the Distribution of Salt Marsh Foraminifera (Great Marshes, Massachusetts). *Journal of Foraminiferal Research,* **25,** no.2, pp.156- 166.

DOUGLAS, R.G., LIESTMAN, J. WALCH, C., BLAKE, G. and COTTON, M.L. 1980. The Transition from Live to Sediment Assemblage in Benthic Foraminifera from the Southern California Borderland. *Pacific Coast Paleogeography Symposium-Pacific Section,* **4,** pp.256-280.

FISHER, R.A., CORSET, A.S. and WILLIAMS, C.B. 1943. The Relationship Between the Number of Species and Number of Individuals in a Random Sample of an Animal Population. *Journal of Animal Ecology,* **12,** pp. 42-58.

FREDA, J. 1991. The Effects of Aluminum and Other Metals on Amphibians. *Environmental Pollution,* **71,** pp. 305-328.

HAYNES, J. and DOBSON, M. 1969. Physiography, Foraminifera and Sedimentation in the Dovey Estuary (Wales). *Geological Journal,* **6,** no.2, pp.217-256.

KONTROVITZ, M., SNYDER, S.W. and BROWN, R.J. 1978. A Flume Study of the Movement of Foraminifera tests. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **23,** pp.141-150.

KRUMBEIN, W.C. and GARRELS, R.M. 1952. Origin and Classification of Chemical Sediments in Terms of pH and Oxidation-Reduction Rotentials. *Journal of Geology,* **60,** pp.1-33.

MOODLEY, L., TROELSTRA, S.R. and VAN WEERING, T.C.E. 1993. Benthic Foraminferal Response to Environmental Change in the Skagerrak, Northeastern North Sea. *Sarsia,* **78,** no.2, pp.129-139.

MURRAY, J.W. 1970. Foraminiferas of the Western Approaches to the English Channel. *Micropaleontology,* **16,** no.4, pp.471-485.

MURRAY, J.W. 1976. Comparative Studies of Living and Dead Benthic Foraminiferal Distributions. In: *Foraminifera 2:* pp.45-109, Eds: R.H. Hedley and C.G. Adams..

MURRAY, J.W. 1982. Benthic Foraminifera: The Validity of Living, Dead or Total Assemblages for the Interpretation of Palaeoecology. Journal of Micropalaeontology, **1,** pp.137-140.

MURRAY, J.W. 1992a. Ecology and Distribution of Benthic Foraminifera: A Review. *Studies in Benthic Foraminifera, Benthos 90, Sendai, 1990.* pp.33-41.

MURRAY, J.W. 1992b. *Ecology and Palaeoecology of Benthic Foraminifera,* pp.1- 397. Longman Scientific and Technical.

MURRAY, J.W. and WRIGHT, C A. 1970. Surface Textures of Calcareous Foraminiferids. *Palaeontology,* **13,** no.2, pp.184-187.

NAGY, J. andALVE, E. 1987. Temporal Changes in Foraminiferal Faunas and Impact of Pollution in Sandebukta, Oslo Fjord. *Marine Micropaleontology,* **2,** pp.109- 128.

NATIONAL RIVERS AUTHORITY, 1992. Water Quality Data. File R19E004. National Rivers Authority, South West Region.

PARKER, F.L. and ATHEARN, W.D. 1959. Ecology of Marsh Foraminifera in Poponesset Bay, Massachusetts. *Journal Paleontology,* **33,** no.2, pp.333-343.

PATTERSON, R.T. 1990. Intertidal Benthic Foraminiferal Biofacies on the Fraser River Delta, British Columbia: Modern Distribution and Paleoecological Importance. *Micropaleontology*, **36,** no.3, pp.229-244.

SHAFER, C.T. 1970. Studies of Benthic Foraminfera in the Restigouch Estuary: 1. Faunal Distribution Patterns near Pollution Sources. *Maritime Sediments,* **6,** no.3, pp. 121-134.

SMART, C. W. and MURRAY, J.W. 1995. Miocene Deep-Sea Benthic Foraminifera from the Atlantic and Indian Oceans: Diversity Patterns and Palaeoceanography. *Revista Espanola De Paleontologia.* pp.59-68.

STUBBLES, S.J. 1993. The Response of Benthic Foraminifera to Heavy Metal Pollution, Restronguet Creek, Cornwall. *Proceedings of the Ussher Society,* **8,** pp.200-204.

STUBBLES, S.J. 1995. Seasonal Variations in Agglutinated Foraminiferan Standing Crops in the Marsh and Tidal Flats of the River Erme. *In: Proceedings of the Fourth International Workshop on Agglutinated Foraminifera.* Eds: M.A. Kaminski, S. Geroch and M.A. Gasinski. Grzybowski Foundation Special Publication no. **3,** pp.265-270.

STUBBLES, S.J., GREEN, J.C., HART, M.B. and WILLIAMS, C.L. 1995. The Effects of Low pH on Living Recent Benthic Foraminifera, (Abstract, 425). *Geological Association of Canada/Minerlogical Associaition of Canada, Victoria,* '95.

STUBBLES, S.J., GREEN, J.C., HART, M.B. and WILLIAMS, C.L. 1996. (in press). Foraminiferal Pollution Signals in the Presence of Heavy Metal Contamination and Acidic Mine Drainage. *Minerals, Metals and the Environment 11.* Prague.

WANG, P. and MURRAY, J.W. 1983. The Use of Foraminifera as Indicators of Tidal Effects in Estuarine Deposits. *Marine Geology,* **51,** pp.239-250.

WILLIAMS, H. F. L. 1995. Foraminiferal Record of Recent Environmental Change: Mad Island Lake, Texas. *Journal of Foraminiferal Research,* **25,** no.2, pp.167-17.

WREN, C.D. and STEPHENSON, G.L. 1991. The Effect of Acidification on the Accumulation and Toxicity of Metals to Freshwater Invertibrates. *Environmental Pollution,* **71,** pp.205-241.