Foraminifera from Restronguet Creek: Monitoring recovery from the Wheal Jane pollution incident

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In 1992, following a period of heavy rainfall, acidic mine water escaped from Wheal Jane tin mine and severely polluted the River Carnon, Restronguet Creek and the Carrick Roads (Fal Estuary). From June 1992, for a period of over four years, a programme of sampling in the inter-tidal sediments of Restronguet Creek was carried out in order to document the disruption to the foraminiferal fauna, the geochemistry of the surficial sediments and the chemistry of the water still entering the estuary. Since that time an extensive water treatment system has been installed that uses a series of "natural" filters. In 2004 this foraminiferal monitoring programme was re-activated using the same sites, the same sampling techniques and the same methodology. It was anticipated that there should be a noticeable recovery of the microfauna. Using samples from February, May and July we sampled across the "spring bloom" and have compared both the species content and abundances with the data generated in the early to mid-1990s. While the balance of taxa has changed slightly the species content remains the same, with no new taxa recorded. The living fauna is dominated by *Haynesina germanica, Elphidium williamsoni* and *Ammonia aberdoveyensis*. Particularly significant is the lack of typical estuarine agglutinated taxa such as *Trochammina inflata, Jadammina macrescens* and *Miliammina fusca*. The geochemistry indicates that the surface muds are now approaching pre-Wheal Jane incident levels, though still containing metals as a result of the natural geological environment of the catchment. Test deformity is reduced, though still present.

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Introduction

In 1992, following a period of heavy rainfall, 50,000 m^3 of acidic mine water and sludge escaped (16th January 1992) from Wheal Jane mine and severely polluted the Carnon River, Restronguet Creek and Carrick Roads (Fal Estuary). From October 1992 until October 1996, a programme of sampling was carried out in the inter-tidal sediments of Restronguet Creek in order to document the disruption to the foraminiferal fauna, the geochemistry of the surficial sediments and the chemistry of the water still entering the estuary. In 2000 an extensive water treatment system was installed and became operational (Younger, 2002). In 2004 this foraminiferal monitoring programme was resumed, using the same locations and methods, in order to assess the level of environmental improvement since the cessation of the original sampling programme.

Prior to this pollution incident there had been no published information on the benthic foraminifera of Restronguet Creek and this has always been a limiting feature of the work on this inter-tidal area. With no data on the distribution of taxa prior to the pollution incident it has been difficult to make firm statements about the impact of the event and the likely time-scale for full recovery. Despite this limitation, Stubbles (1999) reported a recovery in the benthic assemblage towards the end of her studies, probably due to the clean-up measures put in place by the Environment Agency (see later discussion). The immediate post-event clean-up was done using a passive treatment system alongside a conventional lime treatment system previously used in the mine. As this system did not contain the discharge of mine water from Wheal Jane, the establishment of a long term management system involving a passive reed bed storage system was then developed to treat the mine water discharge (Hamilton *et al.*, 1999). This has subsequently been replaced with an active treatment plant comprising a high-density sludge alkali dosing plant, which during its first full winter of operation treated a total of 4,400 million litres of water (Younger, 2002).

Foraminifera as indicators of pollution

The response of foraminifera to polluted environments has been studied for over forty years. The first examples of such work came from areas adjacent to sewerage outfalls on the California coast (Zalesny, 1959; Resig, 1960; Watkins, 1961; Bandy *et al.*, 1964a,b, 1965a,b). This research was expanded to a range of other locations in the 1970s and 1980s (Schafer, 1970, 1973; Schafer and Cole, 1974; Seiglie, 1971, 1975; Bartlett, 1972; Setty, 1976, 1982; Bates and Spencer, 1979; Setty and Nigam, 1984; Ellison *et al.* 1986). In 1991 two significant publications (Alve, 1991; Sharifi *et al.*, 1991) pointed to the impact of heavy metals on the distribution of foraminifera in estuarine environments, as well as introducing the debate on the acquisition of test deformities. The paper by Sharifi *et al.* (1991) was particularly important as it was published in August 1991, just five months before the Wheal Jane pollution incident.

At that time (1991) there was a possibility that:

(1) some foraminifera may be sensitive to pollution;
(2) some foraminifera might be more tolerant of pollution and able to increase in numbers when competition is removed; and
(3) some taxa appear more likely to develop abnormal growth features (misaligned coiling, multiple chambers, etc.) in polluted environments.

In the 1990s there was continued use of foraminifera as indicators of pollution. Yanko *et al.* (1994) linked pollution from heavy metals to changes in the distribution of foraminifera, with Yanko *et al.* (1998) extending this work to the Mediterranean coast of Northern Israel. These authors particularly drew attention to the morphological deformities of

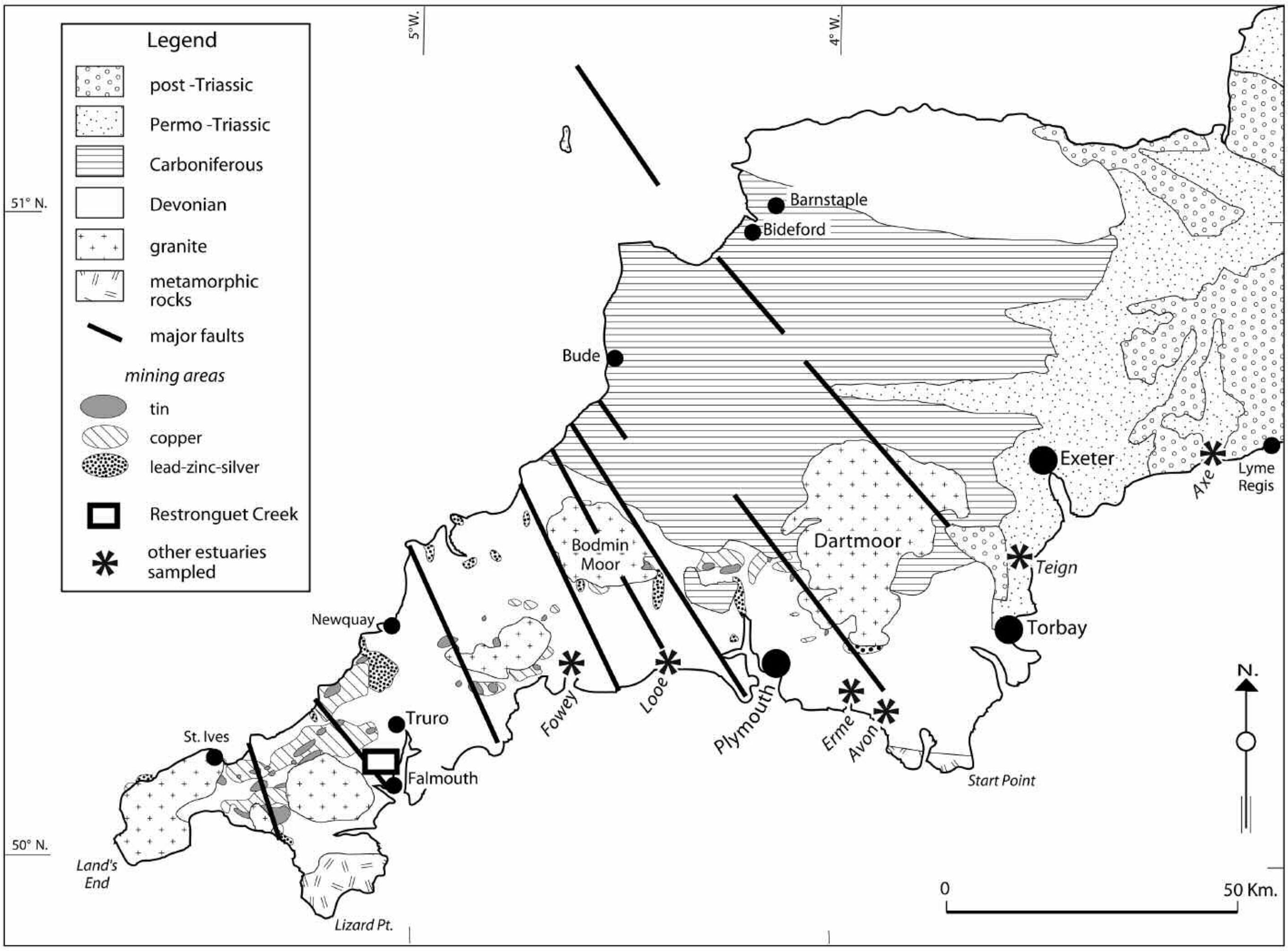

Figure 1. *Outline geological map of South-West England (based on the maps of the British Geological Survey) showing the locations of the major estuaries studied as part of our research. Plymouth Sound and the rivers Plym, Tamar and Lybner have also been intensively studied in the Plymouth area.*

some taxa, including disrupted coiling, aberrant chamber shape and size, additional chambers ('protuberances'), multiple apertures, irregular keels and lack of ornamentation. Such features had also been reported from Sorfjord (W. Norway) by Alve (1991). Work on deformed foraminifera has been continued by Stubbles (1999), Samir (2000) and Olugbode (2004).

In attempting to understand the reasons for test deformity and the link to heavy metal pollution some experimental work on laboratory cultures has been undertaken (Manley, 1997; Yanko *et al.*, 1998; Stouff *et al.*, 1999; Samir, 2000; Scott *et al.*, 2001; Geslin *et al.*, 2002; Saraswat *et al.*, 2004). The uptake of metals by organisms from the environment (bioavailability) is a major area of research (Sharifi, 1991; Bryan and Langston, 1992; Thomson *et al.*, 1984) as are the effects of temperature (Lehtinen *et al.*, 1984; Vranken *et al.*, 1989), salinity (Bengtsson and Bergström, 1987; Stubbles, 1999), presence of organic matter (Verriopoulos and Moraitou-Apostolopolou, 1989) and pH (Schafer, 1970; Reaves, 1986; De Rijk, 1995; Cadre *et al.*, 2003).

Early research on the foraminifera of south-west England estuaries has primarily concentrated on species distributions and the description of taxa (Brady, 1870; Worth, 1900a,b, 1902, 1904; Heron-Allen and Earland, 1916, 1930). More recently Murray (1965, 1971, 1980, 1983, 1991) has described the fauna of Plymouth Sound and the Exe Estuary. The investigation of the Plymouth Sound fauna has been continued by Castignetti (1997) and Manley (1997). Stubbles (1999) also reviewed the faunas of a number of other estuaries in the southwest of England (see Figure 1).

RESTRONGUET CREEK

Restronguet Creek (Figures 1, 2) is a NW-SE oriented arm of the Fal Estuary which is located 10 km south of Truro (Cornwall). The catchment (Figure 2) is drained by the rivers Carnon and Kennal, both of which drain a hinterland with a long history of metalliferous mining (Dines, 1956; Barton, 1969; Burt, 1998; Scrivener and Shepherd, 1998). In a detailed geochemical analysis of Restronguet Creek, Pirrie *et al.* (2003) demonstrated how an increase in metals in the short cores drilled in the estuary and their subsequent decrease marks the mining period of the 18th and 19th centuries. Wheal Jane was, for several years, one of the last working mines in the region but when it was finally abandoned it flooded. Almost all of the abandoned mines in Cornwall are flooded and remain a source of contaminated leachate. Wheal Jane closed in February 1991 and with the cessation of pumping began to fill with water. Following a period of prolonged rainfall the water treatment measures were overwhelmed and 50,000 m^3 (~320 million litres) of untreated water and sludge discharged into the Carnon River over a period of 60 hours.

The Environment Agency have a monitoring station on the River Carnon at Devoran, just above the tidal limit of the estuary. This extensive dataset on the water entering the estuary provides a valuable resource for those working downstream. A number of authors (Schafer, 1970; Reaves, 1986; De Rijk, 1995; Cadre *et al.*, 2003) have studied the relationship between the fauna and the pH of the environment. Figure 3 shows the pH of the water entering the estuary by way of the

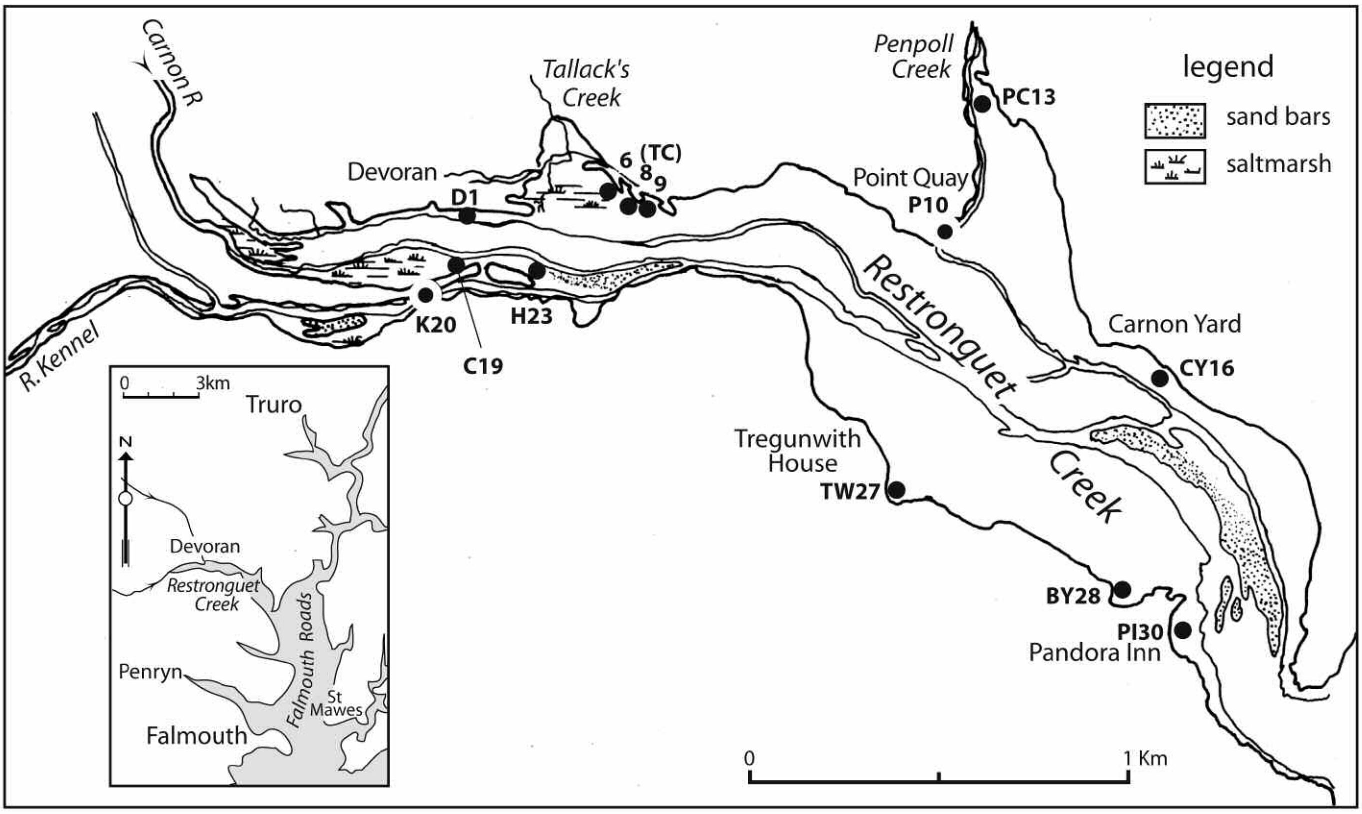

Figure 2. *Location map of Restronguet Creek and adjacent estuaries, showing the sample sites described in the text.*

River Carnon and this shows the pollution incident (February, 1992) and the subsequent recovery to more normal values well before the 2004 sampling programme was undertaken.

At low water an extensive area of mud flats is exposed, with only small isolated areas of saltmarsh. The Kennal River is partly canalised at Carclew and flows in a relatively steep-sided channel. This appears to be the only interference with the natural drainage of the estuary. In 1992, when the earlier sampling programme began, a series of accessible sites were selected along both sides of the estuary. The same sites have been used during the 2004 sampling programme in order that the results of this investigation are directly comparable with those of the 1992-1996 (inclusive) surveys.

Methods

In modern near-shore environments the abundance of foraminifera decreases rapidly with depth within the sediment (Murray, 1991). In order to standardize the volume of sediment that was collected in the field we used a plastic ring of 10 cm diameter that was inserted to a depth of 1 cm into the surface sediments. All the sediment enclosed by the ring was placed in a plastic jar containing buffered formalin. The sample and formalin were thoroughly mixed by gentle shaking. As soon as possible after collection the samples were processed by wet sieving on a 63 μm deep-walled sieve. The residue collected on the sieve was transferred to a bowl and immersed in Rose

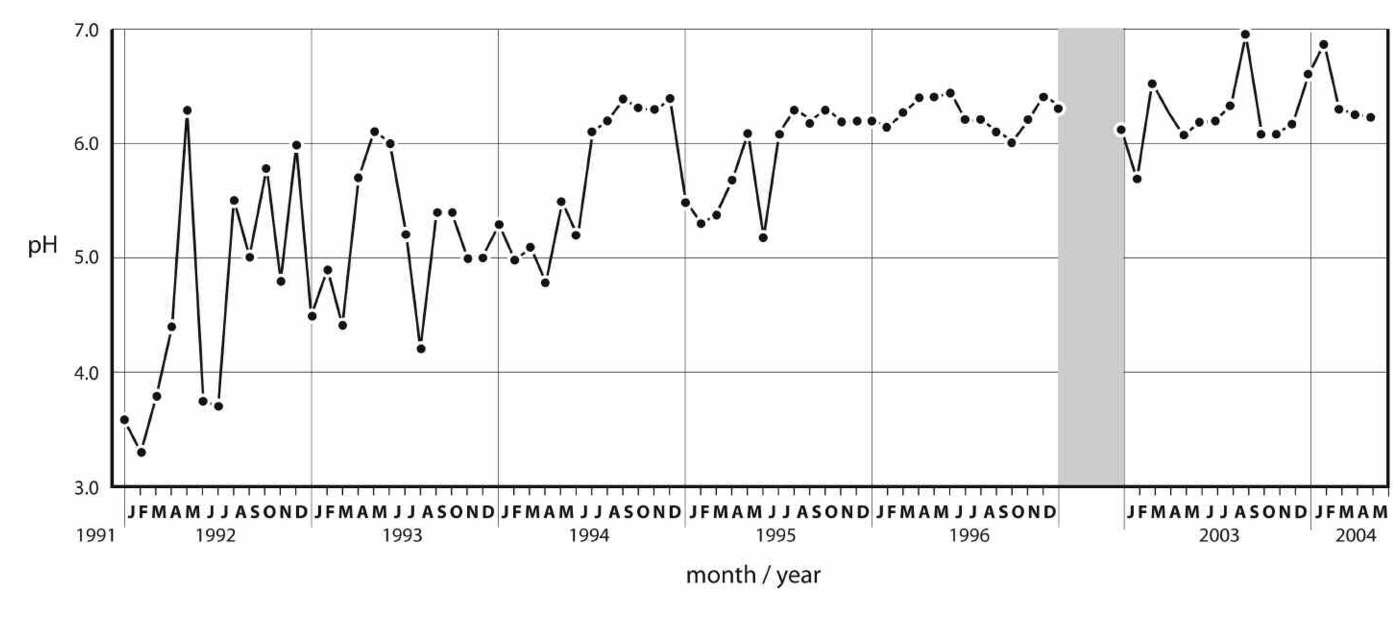

Figure 3. *Graph showing the pH changes with time at the Devoran recording station (data supplied by the Environment Agency).*

Bengal (Walton, 1952) for ~45 minutes to stain the protoplasm within the test of the foraminifera alive at the time of capture (or only recently dead). Further wet sieving on a 63 µm sieve removed the excess staining solution prior to slow drying at 40°C.

Prior to microscope work the dried samples were separated into fractions in a nest of sieves (250 µm, 125 µm, base pan). Counts were based on the different size fractions (>250 µm, 250-125 µm, 125-63 µm) of all the samples.

In the work of Stubbles (1999), there were four sampling periods each year (January, April, July and October), selected to document the over-wintering population, the spring 'bloom' and the summer maximum. In the 2004 survey it was only possible for samples to be collected in early February, early May and mid-July. With the same, fixed locations sampled at almost the same times during the year we suggest that the data are directly comparable over the 1992-2004 period.

DISTRIBUTION OF FORAMINIFERA IN 2004 AND THE CHANGES SINCE 1992

All the data for the 2004 analysis of the foraminifera are presented in Table 1 and Olugbode (2004, appendix 4), with only a summary of the information presented in Figures 4-6. The diversity (= species richness) of living (= stained) species in Restronguet Creek remains low with only three indigenous taxa: *Haynesina germanica* (Ehrenberg), *Ammonia aberdoveyensis* Haynes and *Elphidium williamsoni* (Haynes). We have, tentatively, identified the specimens of *Ammonia* as *A. aberdoveyensis* Haynes (1973) as they appear close to the holotype and paratypes figured by Haynes. There is no single, prominent plug in the umbilicus (typical of *A. batava* (Hofker, 1951)) and the spire, in undeformed specimens, is quite high (not as low as seen in *A. tepida* (Cushman, 1926)). The taxonomy of *Ammonia* is, however, quite problematic (see Hayward *et al*., 2004). In their work, Hayward *et al*. (2004) used some specimens from the Plymouth area (provided by our research group) and they were found to have a molecular type close to both *A. aberdoveyensis* (Type T2U, Hayward *et al*., 2004, table 1) and *A. batava* (Type T3S, Hayward *et al*., 2004, table 1, plate ll).

Stained specimens of *Elphidium crispum* (Linné) and *Quinqueloculina seminulum* (Linné) are also recorded but there is a strong possibility that these individuals have been transported into Restronguet Creek by tidal activity as they are normally marine taxa, rarely found living in estuarine environments. The three dominant taxa vary in proportions along the two sides of the estuary and in the different seasons (Figure 7). *Haynesina germanica* appears to be the dominant taxon throughout much of the year. Figures 4-6 allow comparisons to be made with the data of Stubbles (1999), with the changes between 1996 and 2004 explained in a number of ways, including: (1) the continued impact of the new water treatment system (Younger, 2002) with the final version coming on stream in 2000; (2) the gradual changes in the distribution of taxa re-adjusting to the normalisation of environmental

Standing crop data for 1992-1996 and 2004										
Site	Aut.1992	Win.1993	Spr. 1993	Sum.1993	Aut.1993	Win.1994	Spr.1994	Sum.1994	Aut.1994	Win.1995
D1	barren	barren	90	46	73	barren	no data	303	626	284
TC6	157	470	120	1730	180	292	4	902	1944	1000
TC8	512	1117	2120	3488	302	278	21	2200	788	392
TC9	427	618	1330	820	256	296	10	1112	1792	592
P10	734	1533	3150	1810	340	158	226	764	316	88
PC13	932	940	960	344	74	32	502	983	1084	40
CY16	972	800	2380	1976	328	163	504	2216	1872	392
C19	barren	barren	245	18	6	barren	barren	864	274	no data
K20	barren	barren	barren	barren	barren	barren	barren	no data	52	no data
H23	140	barren	185	54	8	barren	barren	310	674	no data
TW27	1280	372	3544	2712	284	1636	1008	2288	1560	872
BY28	barren	456	4716	1928	748	362	328	3096	392	600
PI30	2856	792	9444	3458	2032	936	1640	3888	432	3280
Site	Spr.1995	Sum.1995	Aut.1995	Win.1996	Spr.1996	Sum.1996	Aut.1996	Win.2004	Spr.2004	Sum.2004
D1	43	1812	286	8	164	4144	1162	237	670	2398
TC6	202	1188	1040	294	3006	3264	1888	838	147	1835
TC8	452	4200	872	360	1648	2856	7240	259	1260	3657
TC9	936	3172	864	488	2208	4400	1808	904	6904	3576
P10	1015	1382	456	132	1440	6720	636	379	1069	723
PC13	752	5800	1896	88	454	4232	1064	63	768	1346
CY16	6328	22976	1480	1444	2360	5904	2384	821	3191	1910
C19	113	640	552	109	145	1926	160	59	190	1383
K20	70	546	158	9	61	1776	522	21	212	389
H23	4	2328	2192	424	220	1852	4168	no data	1547	1360
TW27	3304	4016	1424	6528	2576	6672	3056	511	4022	4358
BY28	2636	5904	3968	3376	2888	3744	3008	726	202	2028
PI30	2376	10048	2536	128	512	3360	2368	386	2611	1060

Table 1. *Standing crop data for 1992-1996 (from Stubbles, 1999) and 2004 (from Olugbode, 2004), which includes all living taxa for each of the sites. "No data" indicates that the site could not be sampled as a result of tidal and/or weather conditions. "Barren" indicates that no living foraminifera were found in a particular sample.*

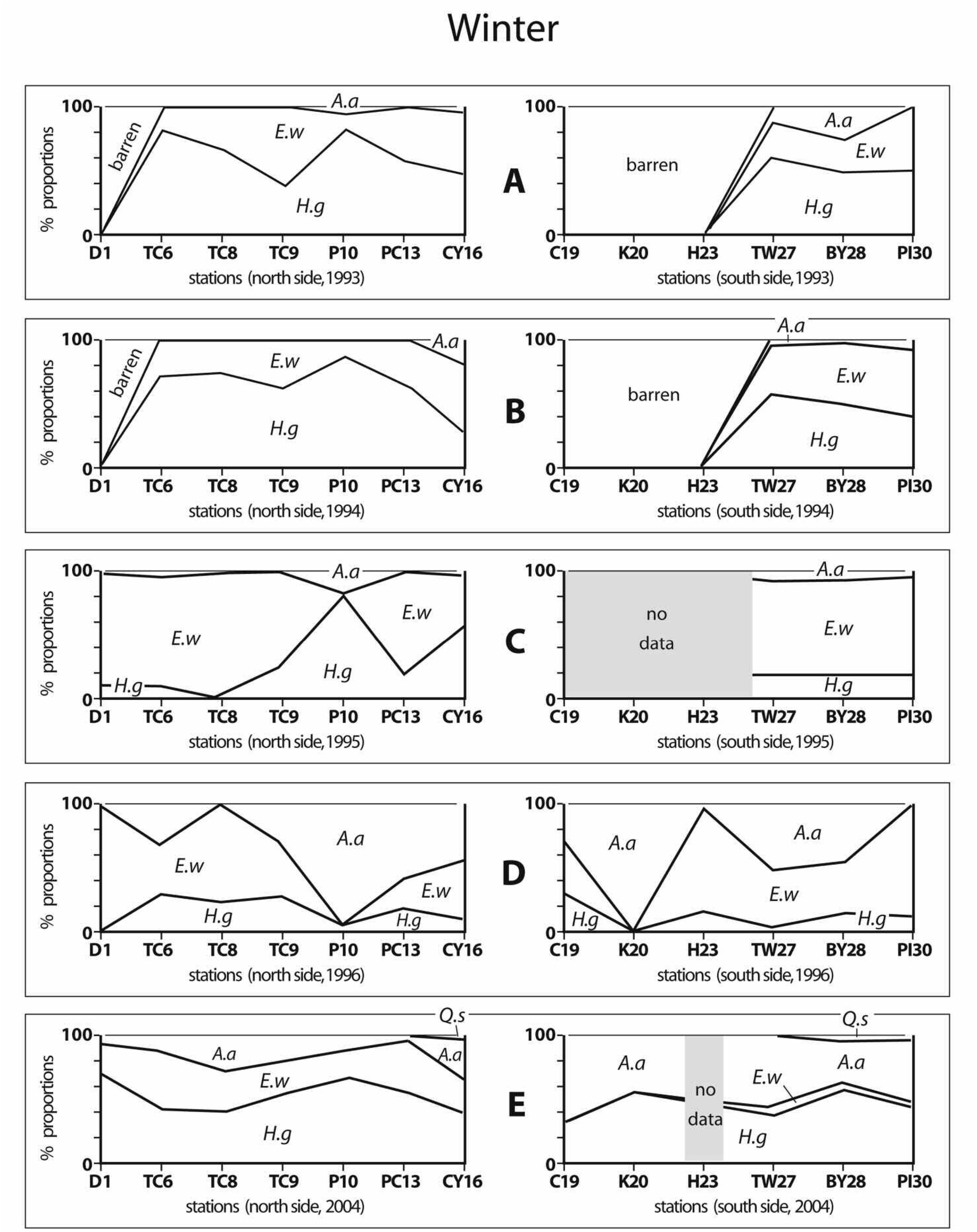

Figure 4. *Distribution of foraminifera in Restronguet Creek: Winter sampling data.* [*A.a* = Ammonia aberdoveyensis; *H.g* = Haynesina germanica; *E.w* = Elphidium williamsoni; *Q.s* = Quinqueloculina seminulum]

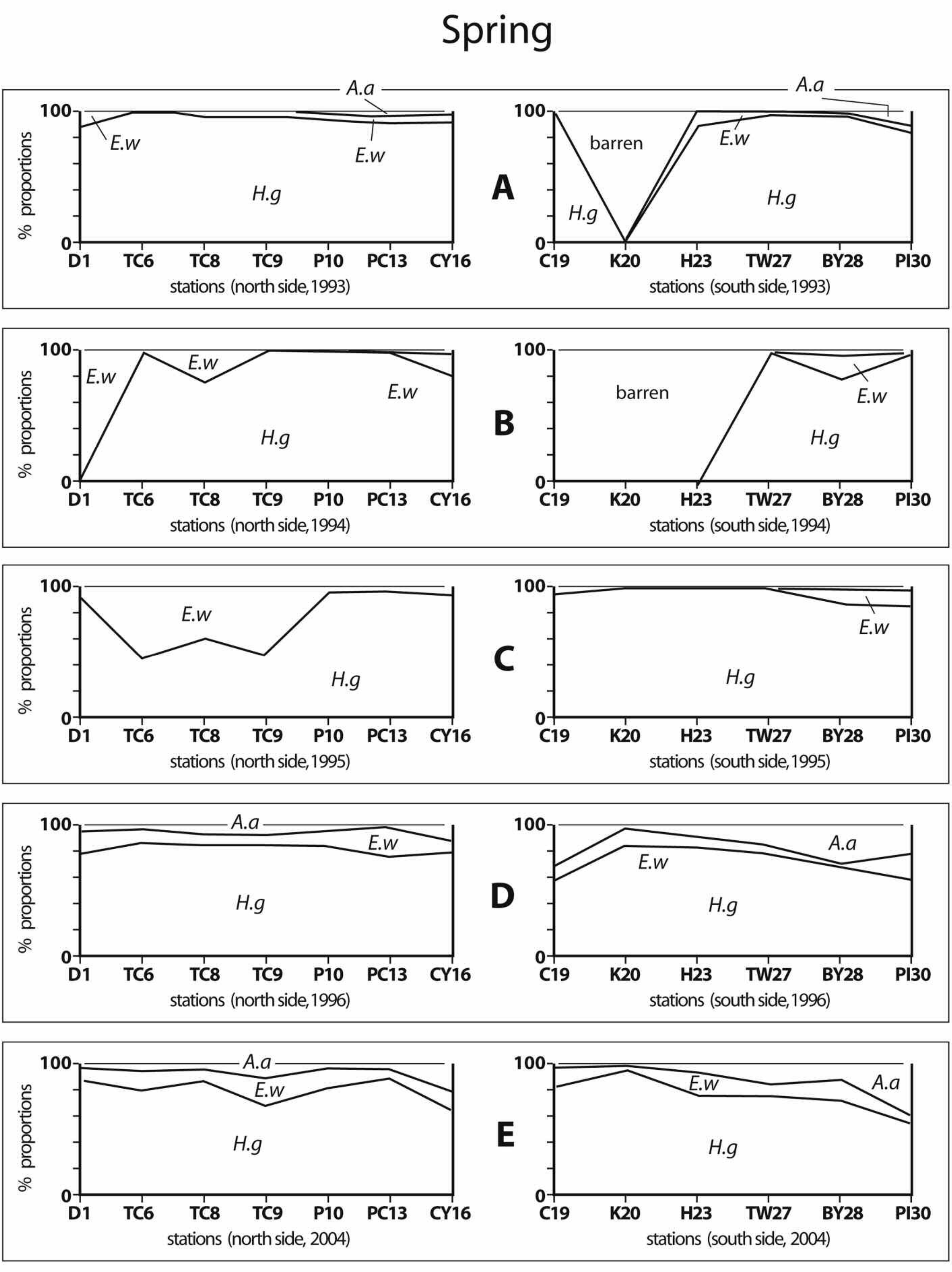

Figure 5. *Distribution of foraminifera in Restronguet Creek: Spring sampling data.* [*A.a* = Ammonia aberdoveyensis; *H.g* = Haynesina germanica; *E.w* = Elphidium williamsoni; *Q.s* = Quinqueloculina seminulum]

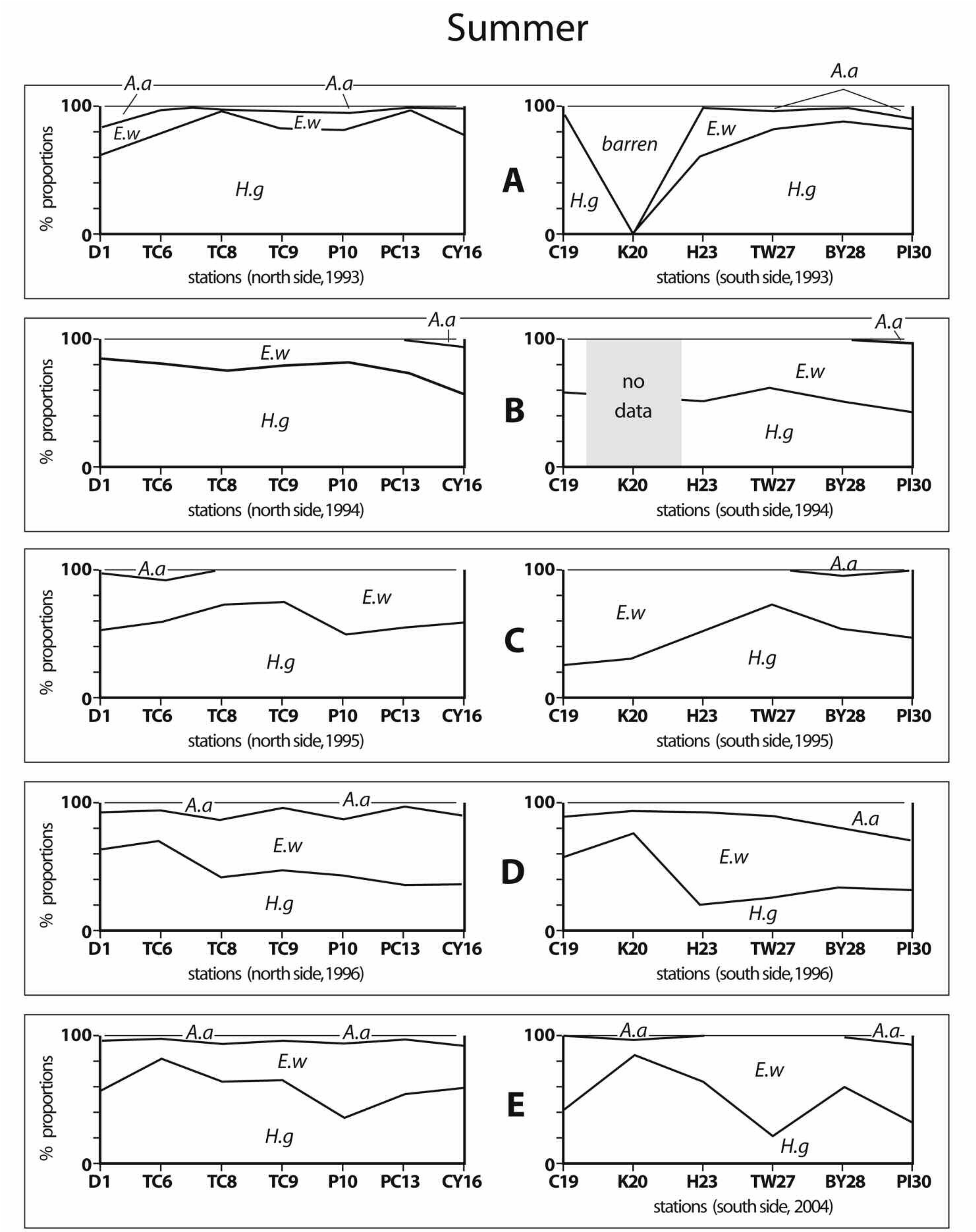

Figure 6. *Distribution of foraminifera in Restronguet Creek: Summer sampling data.* [*A.a* = Ammonia aberdoveyensis; *H.g* = Haynesina germanica; *E.w* = Elphidium williamsoni; *Q.s* = Quinqueloculina seminulum]

parameters following the 1992 Wheal Jane incident; or (3) a response to other factors (e.g., climate change; see Hart and Hart, 2000).

The major difference between Restronguet Creek and other estuaries (Figure 1) in south-west England (Stubbles *et al.*, 1996; Stubbles, 1999) is the total absence of *Trochammina inflata* (Montagu), *Jadammina macrescens* (Brady) and *Miliammina fusca* (Brady). *Trochammina inflata* and *J. macrescens* are associated with upper mudflat and saltmarsh environments in the Fowey, Looe, Erme, Avon and Axe estuaries (Figure 1) but have never been recorded (living or dead) in Restronguet Creek. As sampling only began **after** the Wheal Jane pollution incident it is not known if these species were present in the upper parts of the estuary prior to the contamination. The upper parts of the estuary (Figures 4-6) were barren of foraminifera in 1993 and 1994 (including short cores taken by Stubbles, 1999) and, as these taxa often dominate such environments in many estuaries (e.g., Murray, 1991; Hart and Thompson, 1974), may not have been able to re-colonize the area once excluded by the elevated levels of metal pollution. Restronguet Creek has, however, been affected by high concentrations of metals for many hundreds of years (Pirrie *et al.*, 2003) and this upper mudflat and saltmarsh fauna may never have been present. *Miliammina fusca* is more normally associated with the mid-upper estuarine environment (Stubbles, 1999; Debenay *et al.*, 2000) and the absence of this taxon is not understood. The other taxa recorded in the more seaward parts of Restronguet Creek (e.g., *Fissurina marginata* (Montagu), *Bulimina gibba* (Farnasini), *Brizalina variabilis* (Williamson), *Cibicides lobatulus* (Walker & Jacob) and *Nonion depressulus* (Walker & Jacob)) are almost invariably un-stained and have probably been transported from the more marine parts of the adjacent Carrick Roads.

The population data for 2004 are shown in Figure 7 and these show that the three living, normally estuarine taxa, have their highest populations in the mid-Creek area (Tallack's Creek and Tregunwith House). The upper Creek samples, as might be expected, contain much reduced populations, as do those nearer to Carrick Roads (Penpoll Creek and Pandora Inn). There are quite marked differences between the north and south sides of Restronguet Creek and these are currently being assessed. The distribution of boatyards might be significant in this respect as such areas might be prone to localised pollution and the disturbance of the sediment by boat activity at low tide. In winter months (with a low Sun) the north side of the Creek receives more direct sunlight (and warmth) while the south side of the Creek is probably more shaded by the quite extensive bankside woodland.

Analysis of the population with evidence of growth abnormalities or deformed tests provides some interesting results comparable to those of Jorissen (1988) and Geslin *et al.* (2000). The data for two sample locations (TC8 and TW27) are shown in Figure 8. While there is a general downwards trend over the period from 1993 to 1996, the data for 2004 do not continue the improvement. Indeed the Tallack's Creek (TC8) data for 2004 are comparable to those of 1994. The 2004 data for sample TC8 are not anomalous in comparison to the samples TC6 and TC9, both of which are very close to the location of TC8. In winter 2004 the percentages of the standing crop affected by deformed tests are 19.0% (TC6), 15.4% (TC8) and 12.5% (TC9) respectively. In spring 2004 TC6 records a deformed percentage of 11.6% (compared to 7.9% at TC8) while that recorded at TC9 is 3.1%. In summer 2004 TC8 records the lowest percentage (2.7%) while the other two locations record slightly higher values (TC6 = 5.5% and TC9 = 6.4%).

Figure 8 clearly shows that there is no direct correlation with changing pH (Figure 3) and neither is there a progressive decrease in numbers (or percentages) of deformed tests following the 1992 pollution incident. Further analysis of our data is clearly necessary if the controls on test deformity are to be fully understood. This is because metals are still being derived from the sediments as a result of the oxidation of old particulate sulphidic mine waste (Pirrie *et al.*, 2003).

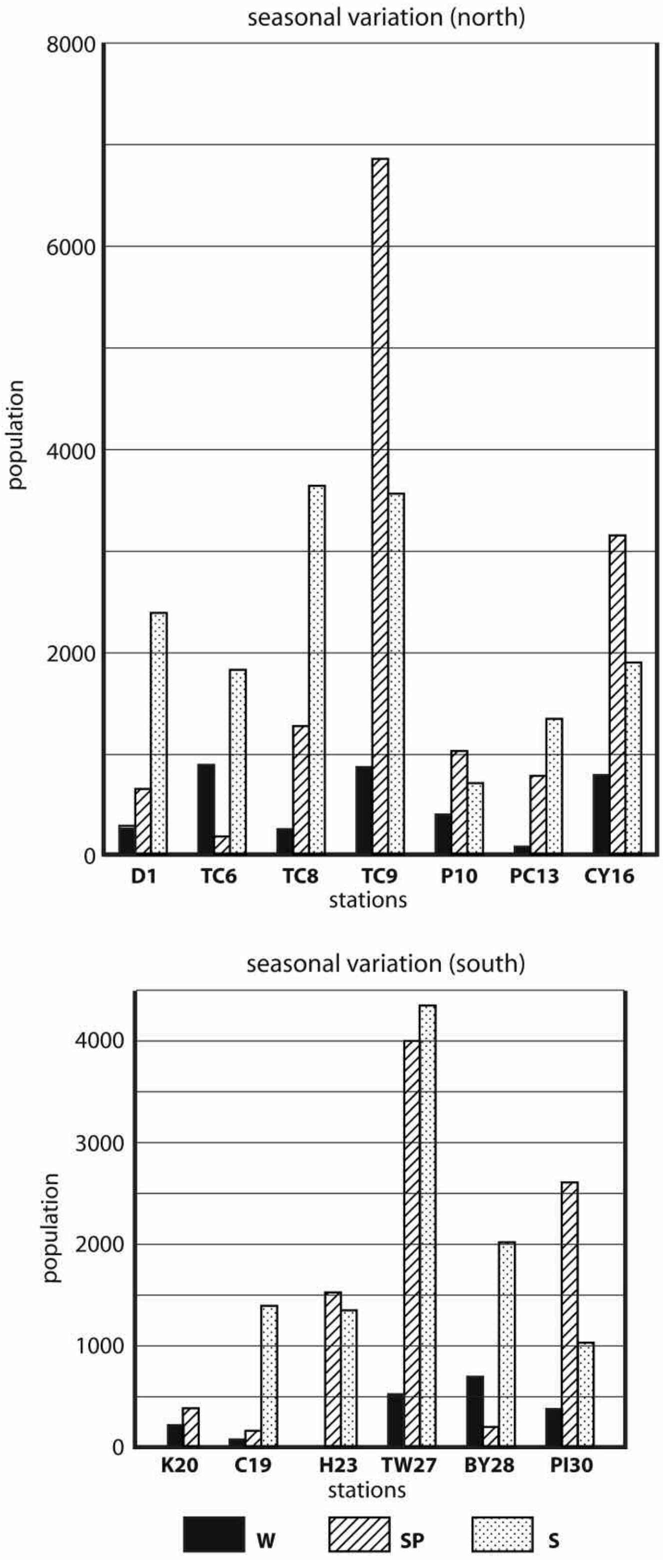

Figure 7. *Population information for the 2004 sampling programme. [w = winter; sp = spring; s = summer]*

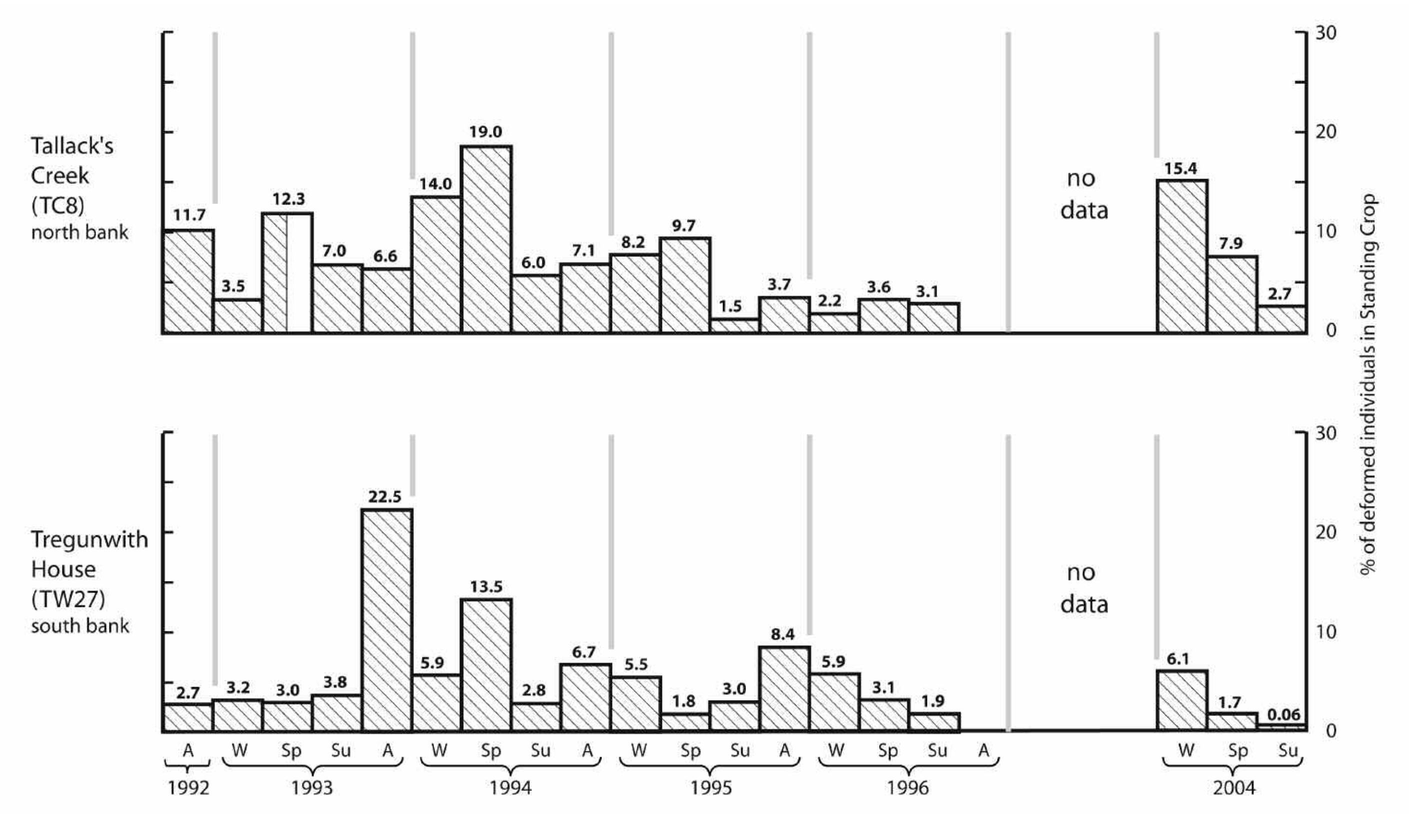

Figure 8. *The percentage of deformed tests in the standing crop for two sample locations: Tallack's Creek (TC8) on the north bank and Tregunwith House (TW27) on the south bank.*

SUMMARY

Following the Wheal Jane pollution incident in January 1992, the distribution of foraminifera in Restronguet Creek was monitored by a sampling programme based on three-monthly sampling of a number of sites on the inter-tidal mudflats of the estuary. This sampling programme was re-started in 2004 with the results confirming the information from the earlier work. No new taxa have colonised the Creek while the transported-in fauna remains largely unchanged. The new water treatment system, which came on line in 2000, may have caused the subtle, or step-wise, changes between the 1996 and 2004 sampling programmes.

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