FORAMINIFERA FROM THE FOWEY ESTUARY, CORNWALL

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Foraminifera are described from the estuary of the Fowey River in South-East Cornwall. Part of the estuary has recently (November 2013) been designated as the 'Upper Fowey and Pont Pill' Marine Conservation Zone and this paper reports the first investigation of the foraminifera (marine and brackish water protists) that live in the area. Assemblages of foraminifera are described from the saltmarsh environments near Lostwithiel, at the head of the estuary, seawards to the sea grass meadows in Polruan Pool. The latter are outside the designated MCZ, though still represent an important marine habitat. The recorded foraminifera are typical of comparable communities along the South-West England coastline. The living foraminifera can be used to identify five assemblages, each with characteristic species. Each of these assemblages shows a close relationship with the salinity and temperature ranges experienced in the area. Deformed foraminifera have been recorded and may be related to the geochemistry of the sediments, which are mainly derived from the Fowey River catchment; an area that was extensively mined in the 19th Century.

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INTRODUCTION

The Fowey Estuary, in S.E. Cornwall, is one of a series of drowned valleys (rias) that characterise the south coast of both Devon and Cornwall. Formed by the rise in sea level after the Last Glacial Maximum, sediments are now building sea-wards, often forming a series of mud flats and saltmarsh environments. Extending from Lostwithiel, where the Fowey River enters the estuary, to the sea at Fowey and Polruan, there are a range of sub-environments including saltmarsh, mudflats, sand banks and – at the seaward end – rocky shores. Within Polruan Pool is an area of eel grass (*Zostera marina*) meadow (Figure 1). The areas bordering the estuary are extensively wooded, including a number of ancient woodlands (Station Wood, Penquite Wood, Great Wood, West Wood, Mendy Pill, Mill Wood and Ethy Wood). The whole of the estuary has been designated as a County Geology Site (previously known as RIGS) due to its geology and unspoilt nature. The area is also within an Area of Outstanding Natural Beauty (AONB) and the higher reaches of the estuary, prior to designation as a Marine Conservation Zone (MCZ), were part of a 'Voluntary Marine Conservation Area' (VMCA). The area at the head of the estuary, near Lostwithiel – which is known as Shirehall Moor – was proposed as a Local Nature Reserve but never fully designated. The important sea grass meadows of Polruan Pool lie outside the earlier VMCA and the present MCZ, though still within the County Geology Site. In November 2013, the Department for Environment, Food & Rural Affairs (Defra) recognised the "*Upper Fowey and Pont Pill Marine Conservation Zone*", building on the existing VMCA. Information on the MCZ are available via the Defra or Natural England websites [*http://www.defra.gov.uk* and *http://www.naturalengland.org.uk*]. The two, spatially separate, areas of the MCZ include the upper reaches of the Fowey Estuary and tributaries (including Pont Pill, Penpol Creek and the Lerryn River). The eel grass meadows in Polruan Pool, which remain outside the MCZ, lie on the east side of the dredged channel that maintains access to the port.

The off-shore and near-shore (including estuarine) environments along the South Cornwall and South Devon coastline have seen some of the pioneering research on modern foraminifera (single-celled protists); see the work of George Montagu (1753-1815), Fortescue Millett (1833-1915), Edward Heron-Allen (1861-1943) and Arthur Earland (1866-1958). There are, however, no published descriptions of the foraminifera that live in the marine and estuarine environments of the Fowey Estuary, although the higher parts of the estuary were previously studied by Stubbles (1999). The off-shore foraminifera of South Cornwall have been described by Millett (1885) and Heron-Allen and Earland (1916, 1930). Other estuaries on the south Cornwall and south Devon coast have been studied for the foraminifera that live in, and on, the sediment surface including Restronguet Creek (Stubbles, 1993,1999; Stubbles *et al.*, 1996; Olugbode *et al.*, 2005), Looe River (unpublished student dissertation), Plymouth Sound (Heron-Allen and Earland, 1930; Murray, 1965; Eddles and Hart,

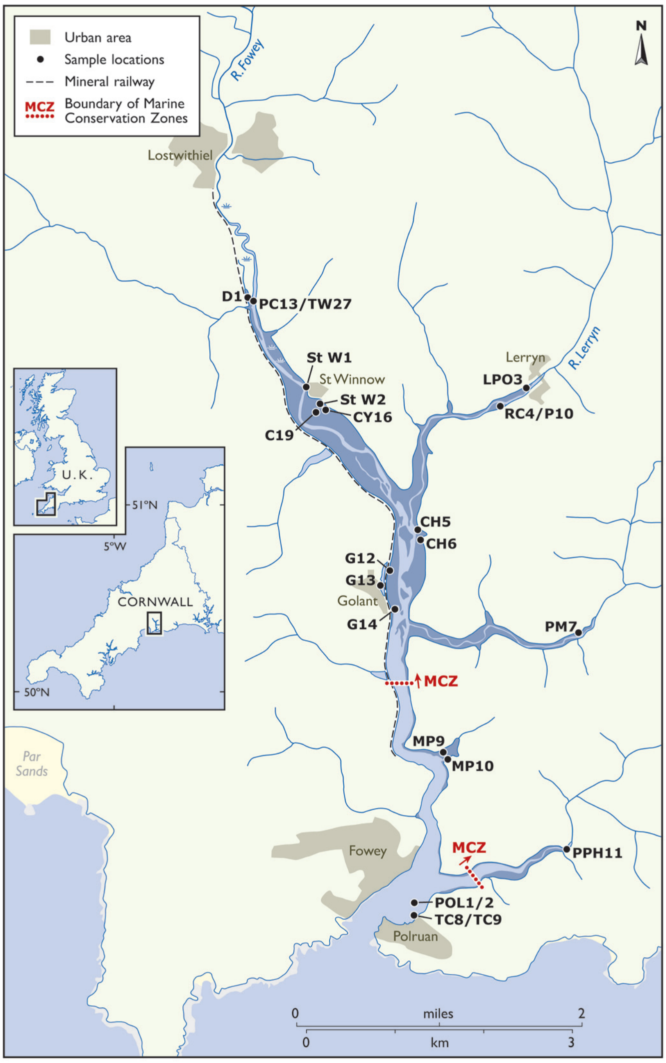

Figure 1. *General map of the Fowey Estuary showing the key features, area of the Marine Conservation Zone and the sampling locations.*

1989; Castignetti, 1993, 1997; Manley, 1997), River Erme (Stubbles, 1995,1999), River Avon (Stubbles, 1999) and River Exe (Murray, 1980, 1983). The only study relating to the foraminifera of local sea grass meadows is that of Sadri *et al.* (2011) in Tor Bay. The latter are now included within the newly established (November, 2013) Tor Bay MCZ.

Geological setting and mineralization

The Fowey River rises on Bodmin Moor and crosses the Devonian rocks of the Variscan Orogenic Belt before entering the estuary at Lostwithiel (Figure 2). The catchment, therefore, includes the granite of Bodmin Moor and the sandstones, siltstones and mudstones of the Looe and South Devon basins (Leveridge, 2011), all of which have undergone low grade metamorphism. The location of mines affecting the catchment of the River Fowey and its principal tributaries (Lerryn River, Cardigan Water, St Neot and Warleggan) are shown in Figure 2.

The area was not as productive as areas further west (Maclean, 1874; Hamilton-Jenkin, 1967). The Pb mines were generally located 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. Treveddoe was also a large mine and reported operations began in the 18th Century, with Cu extraction taking place from 1823 to 1911. During the latter part of the 19th Century and into the 20th Century, Treveddoe was mostly an opencast mine for black tin. In 1943 the mill was rebuilt and used to recover metals from 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; Burt, 1998). East Wheal Rashleigh was worked from 1821 to 1874 for Cu, Mn, Ag and Fe but was probably in production well before that time. The few mines that were working into the 20th Century (Burt *et al.*, 1987) were Pelyn Wood (Sn), St Neot, Hobbs Hill, Tregeale (Sn), Hurstock (Pb), Bodithiel (Pb), Kilham (Sn), Gazeland (W) and Restormel Royal or Iron (Fe). Within the River Fowey catchment there was one smelter at Lostwithiel but by 1805 this was not in use (Barton, 1967) as nearly all metal production had transferred to the smelters at Truro and Penpol (on Restronguet Creek), an area where the bulk of the metal ore was mined. Of the three control sites (Fowey, Erme, Avon) used by Stubbles (1999), historical mining and ore production in the River Fowey catchment was the largest.

Following the Wheal Jane 'incident' on the 16 January 1992 when, during a prolonged period of heavy rainfall, 50,000 m^3 of acidic mine water and sludge escaped from the disused mine workings there has been an on-going interest on the effects of metal pollution on foraminifera in the area (Stubbles, 1999; Olugbode *et al.*, 2005). The Fowey Estuary is fed by a catchment that presently contains no working mines and no record of a comparable pollution 'incident' to that which took place in the Carnon River, Restronguet Creek and Carrick Roads (Fal Estuary). There is, however, a level of metal pollution derived from the natural environment, modern weathering of former mine sites and a re-working of sediments – both on-shore and off-shore – that contain a record of former mining activity (most notably in the 19th Century). While forminifera with 'deformed' tests are recorded in the Fowey Estuary, this is not to the same degree as that recorded in, for example, Restronguet Creek (Stubbles *et al.*, 1996; Stubbles, 1999; Olugbode *et al.*, 2005).

Methods of investigation

In modern near-shore environments living foraminifera are mainly concentrated in the uppermost few millimetres of the sediment (Murray, 1991), though there are examples of species that may live at slightly deeper levels in the sediment (Castignetti, 1996). In order to standardize, as much as possible, the collection of sediment for micropalaeontological analysis a plastic ring (10 cm diameter) was placed into the sediment to a depth of 1 cm (marked by a line on the inside of the ring). The volume of sediment contained in the area (78.5 cm^2) and depth (1 cm) were, hopefully, collected in a consistent manner during the field work. To collect the sediment enclosed within the ring, two methods were employed. At some locations a plastic sheet was gently slid beneath the ring in order to lift out both the ring and the enclosed sediment while, in the majority of locations, it was more effective to use a spoon (or spatula) to scoop out the enclosed sediment. Although it is accepted that this is probably a less precise method of sample collection, it is sometimes the most practical (while diving, or balancing in the very soft mud of a saltmarsh environment). At many sample locations abiotic variables (salinity, temperature, etc.) were also recorded.

All the sediment was placed into plastic pots in the field and preserved in 10% buffered formalin or ethanol. The pots were agitated to ensure thorough mixing, sealed with a screw top and labelled. These samples were wet-sieved in the laboratory using a wide diameter, deep, 63 µm sieve to remove the clay and fine silt grade material. The collected residue was then placed in a bowl of rose Bengal (organic stain), at a concentration of 1 g per litre de-ionized water, for 3 hours. The time taken for staining, and views on its efficacy, vary from the 10 minutes suggested by Walton (1952) to the 14 days proposed by the FOBIMO project (Schönfeld *et al.*, 2012; Schönfeld,

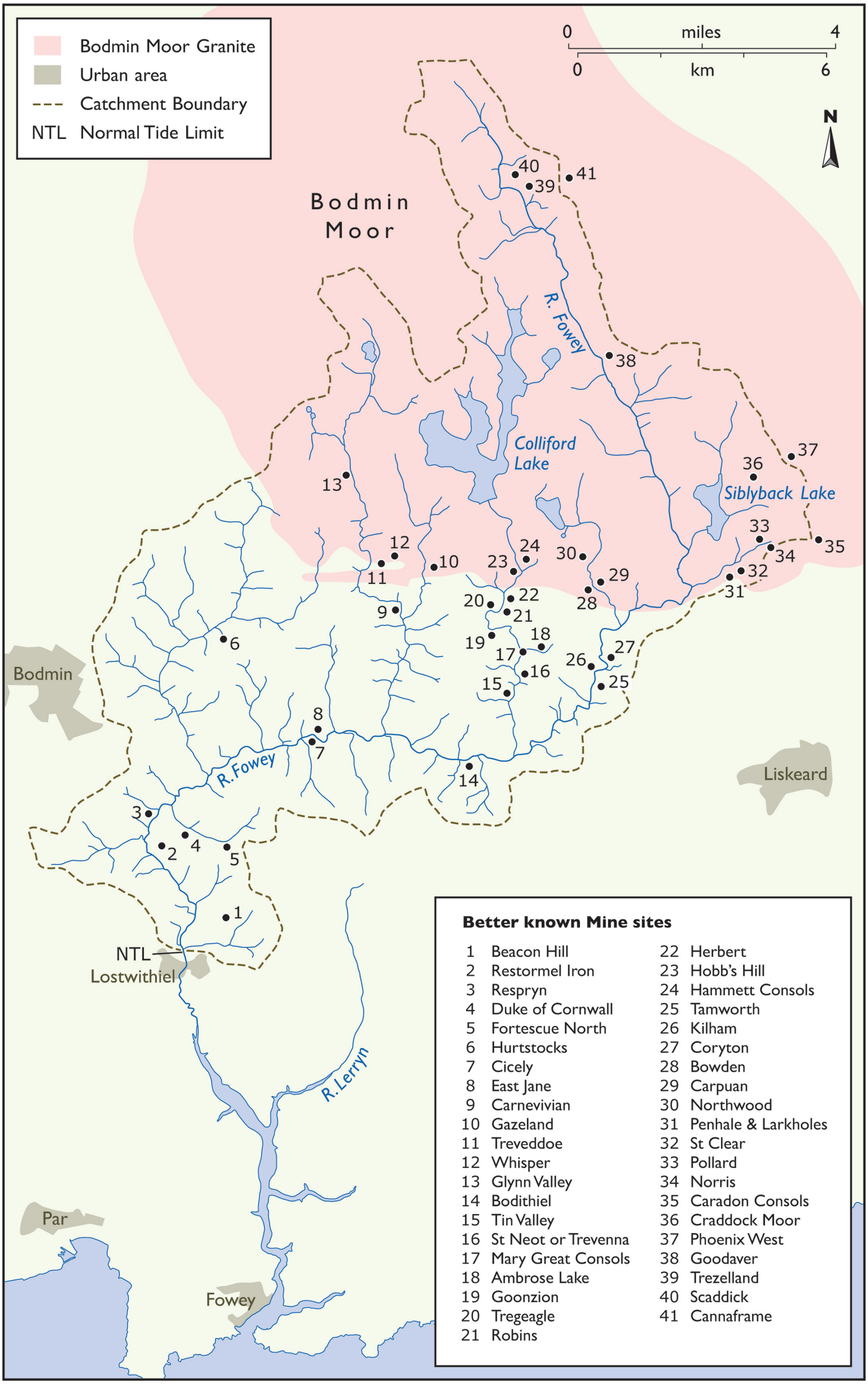

Figure 2. *Outline map of the Fowey River catchment, the outcrop of the Bodmin Moor Granite and the location of principal mining centres.*

2014). After soaking, the sample was again washed on a 63 µm sieve until no stain was colouring the water. After filtering, each sample was dried in a cool (<40ºC) oven. Residues were studied using the following size fractions: >500 µm, 500-250 µm, 250-150 µm and 150-63 µm. The <63 µm residue was also checked in case something not present in the other size fractions was being systematically missed. In some samples, this fine-grained sediment contained testate amoebae (thecamoebians) and these are the subject of a separate investigation (see Stubbles, 1999). After picking the foraminifera (both stained and un-stained), ostracods and other macrofaunal debris onto gridded slides, some specimens were selected for imaging using a scanning electron microscope. Specimens were coated with 8-10 nm of gold and the digital image collected using a voltage of 15 Kv at a working distance of (usually) 20 mm.

Sediment samples for geochemical analysis were collected at some sites by using a spatula to remove the oxidised layer (maximum depth 0.5 cm) and placed it into paper (craft) bags. The samples were removed and dried as soon as possible, again in a cool (<40ºC) oven. The samples for analysis were gently disaggregated prior to weighing, with 0.5 g separated from each sample. To this was added 10 ml of 1M HCl, after which the sample was placed on a shaking table for 2 hours and then centrifuged for 5 minutes. The supernatant was decanted into volumetric flasks and made up to 50 ml. These solutions were analysed for Cu, Zn, As, Fe, Pb, Ni, Ca and Cd using flame (air-acetylene) AAS (atomic absorption spectrometry). For the analysis of Sn, Al and Cr a nitrous oxide acetylene flame was used. Organic carbon and nitrogen were measured at Plymouth Marine Laboratory using a Carlo Erba NA-1500 Series 2 analyser, pre-set at 1,030ºC using the method of Verado *et al*. (1990). Grain size analysis was undertaken using a 'Malvern Mastersizer' laser detector.

The Fowey Estuary

The Fowey Estuary is dominated by tidal mud flats (Figures 1, 3a-c) that are colonised, in discrete areas, by fucoid algae. Areas of saltmarsh are quite restricted and only accessible in Shirehall Moor [SX 108 581] near Lostwithiel. The eastern shore is largely tree-lined but accessible at a number of locations (e.g. St Winnow, Lerryn, Mixtow Pill, etc.). The western shore is mostly clear of woodland, in order to accommodate the mineral railway that is used to transport china clay to the port at Fowey. This mineral railway is private property and this causes access problems which restrict sampling to the area immediately adjacent to Golant. Dredging, to maintain the port of Fowey, is the reason for the lack of MCZ designation in the lower estuary in the vicinity of Fowey, Bodinnick and Polruan although the sea grass meadows are outside the dredged area. As indicated in Figure 1, samples have been collected from a number of locations along the length of the estuary. All those from the upper estuary were collected at the mid-tide level from Shirehall Moor, St Winnow, the Lerryn River, Cliff, Golant, Middle Penpol, Mixtow Pill, and Pont. Three of these locations (Lerryn River, Middle Penpol and Pont) are on tributaries to the main estuary and, as such, are also in 'higher' mud-flat environments.

The foraminifera have been identified using Heron-Allen and Earland (1916, 1930), Murray (1968a, b, 1970, 1971, 1979) and Castignetti (1997). Almost all of the taxa recorded in the Fowey Estuary are well known and only a brief taxonomic list is included in the Appendix.

Shirehall Moor, near Lostwithiel, was formerly used as a refuse tip, but has been partially cleared and paths created. At the southerly extension of the reserve there is a promontory between the Fowey River and an un-named side creek. Sample PC13 was collected on this promontory (Figure 3a), with sample TW27 two metres to the south. Sample D1 was collected on the side of the small creek ~7 m to the west of PC13/TW27. During the time when Sheila Stubbles was undertaking her research, this area was not accessible and St Winnow provided the first available location for sampling.

At St Winnow, close to the church, there is a small boat repair yard and over-wintering boat storage (Figure 3b). Stubbles (1999) collected two samples (StW1, StW2) upstream and downstream of the slipway. In 2014 additional samples were collected, with CY16 equating with StW2 and C19 being located 5 m to the SW, further out on the mud flats (approximately 0.25 m below mid-tide).

The sample locations at the head of Lerryn Creek are from within a sparsely built-up area. LP03 was collected close to the river (Figure 3c), downstream of the road bridge while RC4 and P10 were collected from an identical location at the end of an access road along the south bank of the creek. At Cliff House (samples CH5, CH6) there are only a few houses. A small hamlet surrounds the bridge area at Middle Penpol (sample location PM7) and has a consent-to-discharge station.

The two mud-flat sample locations (MP9 north of the creek and MP10 south of the creek) at Mixtow Pill are immediately opposite the china clay wharves and could, potentially, be impacted by clay spillage (though none has been reported recently). A pontoon has been constructed to accommodate the numerous leisure and small commercial boats moored at the Pill.

Sample location PPH11, at the head of Pont Pill, is in a conservation area owned by the National Trust and has limited vehicular access. Pont Pill is a separate part of the Upper Fowey and Pont Pill MCZ (see Figure 1).

On the west bank of the estuary the only real access is at Golant as, elsewhere, the mineral railway line follows the shoreline. Sample locations G12 and G14 are in the main channel, with – compared to sites further upstream – the surface sediments being fine-medium, slightly muddy, sand. Sample location G13 was collected from within a small basin that is often occupied by small fishing craft. Golant is quite densely populated and there are a number of boat repair yards.

In Polruan Pool, opposite the town of Fowey, there is a small area of sub-tidal sea grass. Sea grasses are marine angiosperms (plants) that, in the mid-Late Cretaceous, 'migrated' from the land into shallow-water marine environments (Brasier, 1975; den Hartog, 1977; Lee and Anderson, 1991; Sen Gupta, 2002; Murray, 2006; Foden and Brasier, 2007). They represent a distinct habitat and the recently published investigation of the sea grass meadows in Tor Bay (Sadri *et al*., 2011) has identified the presence of abundant foraminifera in both the meadow and the adjacent sea floor sediments. This investigation of the sea grass meadow of Polruan Pool – which consists of the 'eel grass' *Zostera marina* (Linné, 1753) – must be regarded as a pilot study, but there are direct comparisons with the assemblages of foraminifera associated with the Tor Bay meadows. We have not yet completed a full survey of the foraminifera throughout an annual cycle but the species encountered are well known in the region (Millett, 1885; Heron-Allen and Earland, 1916, 1930; Castignetti, 1997; Manley 1997; Sadri *et al*., 2011, figure 4).

The samples used in this investigation are from the sea grass root systems and fronds (POL1), sediments within the sea grass meadow (POL2) and sediments collected from the foreshore at Polruan at low tide (TC8, TC9). The samples from within the sea grass meadow in Polruan Pool were collected by diving (Claire Hoddinott, assisted by Liz Clarke) in both summer (July) and autumn (October) 2013. On each occasion the samples collected included the intra-meadow sediment, sediment associated with the root systems of the *Zostera marina* which was extracted carefully by pulling on the grass and the fronds themselves which were collected by cutting just above the sediment surface. These samples were retained in sea water, transported to Plymouth and fixed in buffered formalin before staining and sieving. Very few foraminifera were found to be stained, but this is quite normal for late in the year. The assemblage in all samples was found to be almost identical to those recorded in comparable samples from Tor Bay by Sadri *et al*. (2011).

Figure 3. *Field locations. (**a**) Sample collection (location PC13) at the southern end of Shirehall Moor, Lostwithiel. (**b**) Looking upstream from St Winnow church. (**c**) Looking upstream at Lerryn, with sampling locations RC4 and P10 just behind the camera and sample location LP03 on the north side of the stream close to the road bridge in the distance.*

Distribution of foraminifera

While the foraminifera of the Fowey Estuary (Figures 4, 5) have never been described, aside from the un-published work of Stubbles (1999), the assemblages contain all the taxa that one would expect on the south coast of Cornwall and Devon, comparable with those described by Heron-Allen and Earland (1916, 1930), Murray (1965, 1970), Castignetti (1997), Manley (1997), Olugbode *et al.* (2005) and Sadri *et al.* (2011). The distribution of taxa shown in Figure 6 is complicated by the placing of samples from Lerryn, Middle Penpol and Pont Pill into a sequence attempting to plot data along the length of the estuary. It is possible, even so, to recognise 5 assemblages all of which appear to be controlled by the salinity and temperature data shown in Table 1. The assemblages are:

1) Saltmarsh: *Jadammina macrescens* with *Trochammina inflata* (PC13, D1, TW27).
2) Higher estuary (1): *Miliammina fusca* with *Haynesina germanica* and *Elphidium williamsoni* (StW1, StW2, LP03, RC4).
3) Higher estuary (2): *H. germanica* with *M. fusca* and *E. williamsoni* (CY16, C19, P10, PM7, PPH11, CH5, CH6).
4) Lower estuary: *H. germanica* with *M. fusca, E. williamsoni* and *Ammonia* sp. cf. *A. aberdoveyensis* (G12, G13, G14, MP9, MP10).
5) Marine estuary: *Elphidium crispum* and *Ammonia* sp. cf. *A. aberdoveyensis* with *Quinqueloculina seminulum, Cibicides lobatulus* and *Astigerinata mamilla* (POL1, POL2, TC8, TC9).

As indicated by Stubbles (1999), there are seasonal variations in the distribution of taxa and in the standing crops recorded. Her sampling did not include Shirehall Moor (PC13, TW27, D1) as the site was being used for waste disposal at the time. These three samples contain only three living taxa: *Balticammina pseudomacrescens, Jadammina macrescens* and *Trochammina inflata*. In all the samples studied *J. macrescens* was dominant, with *T. inflata* being somewhat rare. The only other microfossils present in these samples were rare species of *Leptocythere* (Ostracoda). This assemblage (Assemblage 1 in Figure 6) is typical of such saltmarsh settings in both South-West England and elsewhere (Murray, 1968a, 1973, 1991; Hart and Thompson, 1974; De Rijk, 1995a, b; De Rijk and Troelstra, 1997; Gehrels and van de Plassche, 1999; Culver and Horton, 2005; Horton and Edwards, 2006; Horton and Murray, 2007; Leorri *et al.*, 2010). Off-shore North Carolina, Horton and Culver (2008) also record the presence of *Ammobaculites* spp. and *Arenoparrella mexicana*, but these taxa are not recorded in the Fowey Estuary. Hayward (2014) has recently described comparable *J. macrescens*–dominated assemblages from low-salinity salt marsh environments in New Zealand. In that paper, Hayward uses the generic name *Entzia*, following the suggestion of Filipescu and Kaminski (2011). *Entzia*, designated by Jenó (Eugen) von Daday in 1883-1884 from a saltmarsh in Transylvannia (Romania), comes from a continental location – far removed from a marine environment. While *Jadammina* and *Entzia* clearly look similar, the name *Jadammina* is retained here pending genetic confirmation that the two are co-generic.

The distribution of species, and the identification of the five assemblages shown in Figure 6, is complicated by the configuration of the Fowey Estuary. Estuaries such as the Looe River (Cornwall), River Erme (Devon), River Avon (Devon) and River Axe (Devon) all trend N-S but have no comparable tributary systems. Samples from Lerryn (LP03, RC4, P10), therefore, have some species typical of saltmarsh environments and physical characteristics (see Table 1) in common. Assemblage 1 has also been recorded in the various tributaries of the Fal Estuary: near Devoran [SW 820 389] in Restronguet Creek, near Tresillian [SW 858 452] in the Tresillian River and near Ruan Lanhorne [SW 886 417] in the River Fal. Assemblage 1 is also recorded in the Looe River, River Erme, River Avon, River Axe and off-shore Jersey (Consolaro *et al.*, 2014), just above a distinctive layer of peat that has been radio-carbon dated. This record of Assemblage 1 is short-lived, as the post-glacial rise in sea level in that area was very rapid (Massey *et al.*, 2008).

The occurrence of *J. macrescens* and *T. inflata* in sample G12 looks anomalous and appears to indicate derivation from a nearby saltmarsh or considerable transport. The latter option

Assemblage	Winter/Spring			Summer/Autumn		
1-2	Head of Estuary <5‰	5-7˚C	LP03, RC4 PC13, D1, TW27, P10	Head of Estuary <5‰	6-10˚C	TW27, D1 PC13
2-3	Upper Estuary 5-18‰	5-9˚C	StW1, StW2, PPH11, PM7	Upper Estuary 5-18‰	6-12˚C	LP03, RC4, P10
3	Mid-estuary 18-25‰	8-9˚C	CH5, CH6, C19, CY16	Mid-estuary 18-25‰	9-13˚C	StW1, StW2, PPH11, CH5 CH6, C19, CY16
4	Lower Estuary 25-35‰	9-11˚C	MP9, MP10, G12, G13 G14	Lower Estuary 25-35‰	10-16˚C	MP9, MP10, G12, G13, G14
5	Marine Estuary ~35‰	10-12˚C	POL1, POL2, TC8, TC9	Marine Estuary ~35‰	12-16˚C	POL1, POL2, TC8, TC9

Table 1. *Salinity and temperature data for the five assemblages, together with an indication of the samples that provided the information.*

is unlikely as the wholesale transport of empty tests is not widespread elsewhere in the estuary. Transported-in taxa are relatively rare and this is either due to the shape of the estuary or, perhaps, the dredging activity near Fowey. Sheila Stubbles collected a short core from the upper estuary in the 1990s and showed that the proportion of 'introduced' species has changed (historically) as between 33 cm in the core and the base at 40 cm – an interval that would pre-date dredging (which began in 1904) – was greater than after that date.

Samples collected from the inter-tidal muds close to the church in St Winnow contain an assemblage dominated by *Haynesina germanica* (Ehrenberg) and *Elphidium williamsoni* Haynes with significantly high numbers (especially in winter) of *Miliammina fusca* (Brady). At this location *J. macrescens* was very rare and *T. inflata* not recorded. *M. fusca* is a rather unusual, and occasionally uncommon, species that – though with a finely agglutinated wall structure – coils in a milioline 'style'. In some locations (e.g. Erme Estuary, Devon) this species is known to incorporate significant numbers of diatoms into its wall and this is also true in the Fowey Estuary. Hayward (2014, figure 2) shows *M. fusca* occupying a mid-high estuary location (salinity ~10-30 psu) and this is also true in the Fowey Estuary. *M. fusca* is the most numerous species in StW1, StW2, LP03 and RC4 (Figure 6).

Samples from the Lerryn River, close to the village, contain few foraminifera, although *M. fusca* and *H. germanica* are recorded. Samples from Cliff, Middle Penpol and Pont contain very similar assemblages, including *H. germanica, E. williamsoni* and *M. fusca*. In the samples from Golant and Mixtow Pill, which are in the main channel of the estuary, there is an increasing marine influence as indicated by the presence of stained (= living) *Ammonia* sp. cf. *A. aberdoveyensis* Haynes.

The samples of sea grass fronds and root systems (POL1), collected in the summer, contained only *Elphidium crispum* (Linné), though none stained as if living (unlike the situation reported in Tor Bay by Sadri *et al*., 2011). The sediments from within the sea grass beds (POL2) and the foreshore (TC8, TC9) contain the most diverse, marine, assemblage of any samples, unsurprising in terms of the location. There is a clear need to collect a seasonal suite of samples from this area in order to determine if the spring 'bloom' also records high numbers of epiphytal *E. crispum*, comparable to those recorded in the sea grass meadows of Tor Bay (Sadri *et al*., 2011).

	Restronguet Creek (ppm)	Fowey Estuary (ppm)
Al	925 - 1,425	180 - 510
Fe	550 - 1,250	140 - 3,450*
Cu	525 - 825	10 - 140
Pb	25 - 150	10 - 25
Ni	10 - 20	10 - 15
As	105 - 310	No data
Zn	1,010 - 1,800	20 - 320

* Includes a reading from sample PM7 (near the discharge station).

Table 2. *Geochemical data for the Fowey Estuary and Restronguet Creek.*

GEOCHEMISTRY

Results of the geochemical analysis are shown in Figure 7, in which the sample locations on the eastern shore are plotted separately from those on the west. The samples from Golant (G12, G13, G14) would fall, in terms of location, between those from Cliff (CH5, CH6) and Mixtow Pill (MP9, MP10) and the geochemical data are in broad agreement with that interpretation. The exception appears to be the Middle Penpol sample (PM7) and this must be due to either the geology of the local catchment or the discharge station (Table 2).

The levels of recorded metals in the sediments of the Fowey Estuary are, however, much less than the values recorded in Restronguet Creek by Stubbles (1999) and Pirrie *et al*. (2003). In almost every sample studied, the values recorded in Restronguet Creek demonstrate the legacy of the Wheal Jane pollution incident, with the Fowey Estuary only reflecting the background values coming from the mineralised catchment. The possible relationship between the geochemistry of the samples and the distribution of deformed foraminifera is explored below.

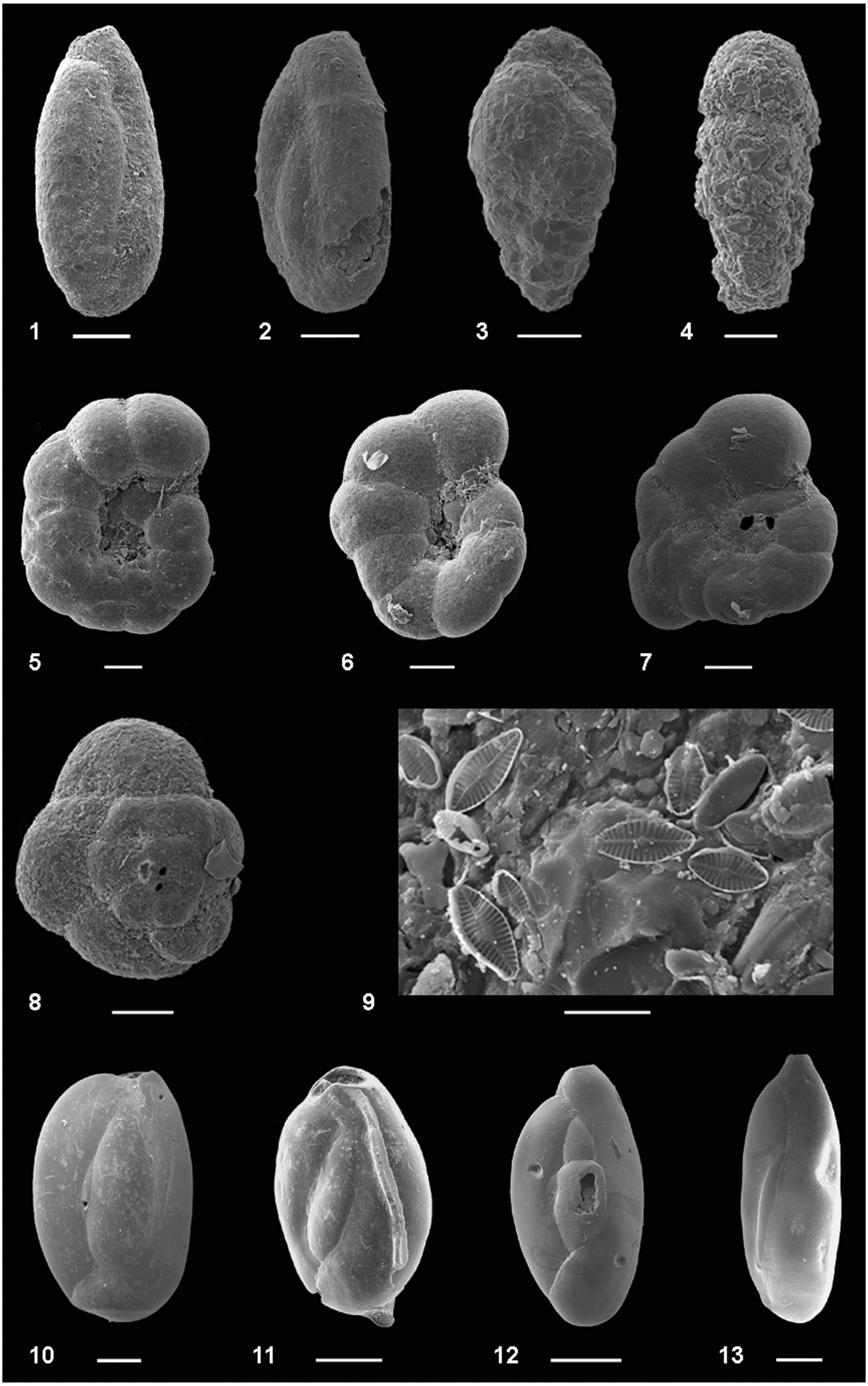

Figure 4. *Illustration of some of the more important species of foraminifera found in samples from the Fowey Estuary.* ***(1)*** Miliammina fusca, *P10.* ***(2)*** Miliammina fusca, *PC13.* ***(3)*** Eggerelloides scaber, *POL1.* ***(4)*** Eggerelloides *sp. cf.* E. scaber, *POL1.* ***(5)*** Balticammina pseudomacrescens, *TW27.* ***(6)*** Jadammina macrescens, *slight deformation, TW27.* ***(7)*** Jadammina macrescens, *slight deformation, PC13.* ***(8)*** Trochammina inflata, *TW27.* ***(9)*** *Detail of surface of* Trochammina inflata *showing presence of numerous diatoms (mainly* Planothidium delicatulum*).* ***(10)*** Quinqueloculina seminulum, *POL1.* ***(11)*** Quinqueloculina *sp. cf.* Q. lata, *POL2.* ***(12)*** Quinqueloculina oblonga, *POL2.* ***(13)*** Quinqueloculina oblonga, *POL1. All scale bars = 100 μm, except 4 = 50 μm, 9 = 10 μm, 12 = 200 μm.*

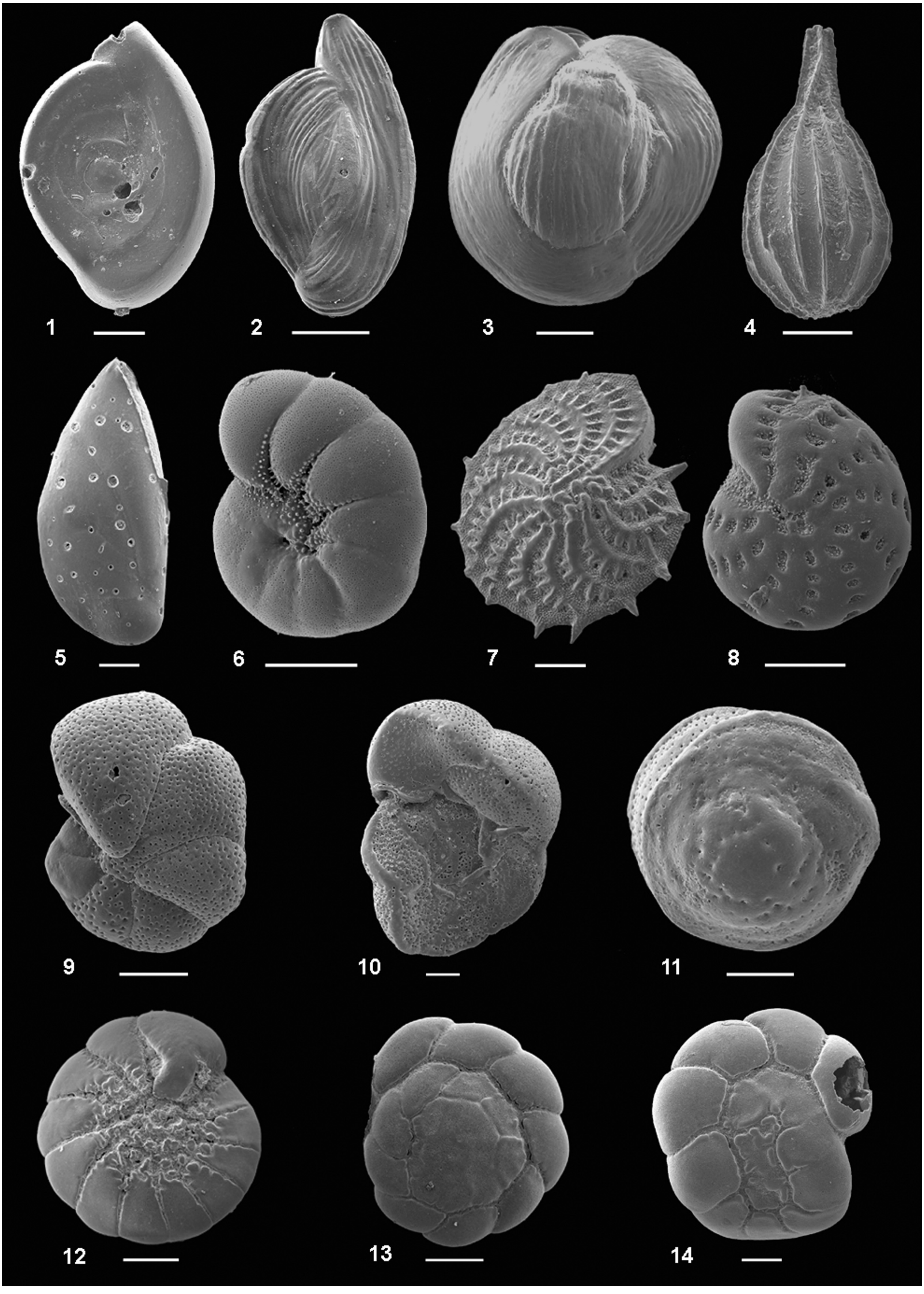

Figure 5. *Illustration of some of the more important species of foraminifera found in samples from the Fowey Estuary.* ***(1)*** Spiroloculina *sp. cf.* S. rotunda, *POL1.* ***(2)*** Quinqueloculina cliarensis, *POL1.* ***(3)*** Quinqueloculina bicornis, *POL2.* ***(4)*** Lagena *sp. cf.* L. substriata, *POL1.* ***(5)*** Astacolus *sp. cf.* A. crepidulus, *POL1.* ***(6)*** Haynesina germanica, *P10.* ***(7)*** Elphidium crispum, *POL1.* ***(8)*** Elphidium williamsoni, *C19.* ***(9)*** Cibicides lobatulus, *POL1.* ***(10)*** Cibicides lobatulus, *POL2.* ***(11)*** Astigerinata mamilla, *POL1.* ***(12)*** Ammonia *sp. cf.* A. aberdoveyensis, *POL1.* ***(13)*** Ammonia *sp. cf.* A. aberdoveyensis, *POL1.* ***(14)*** Ammonia *sp. cf.* A. aberdoveyensis, *deformed growth, POL1. All scale bars = 100 µm, except 2, 12, 13 = 200 µm.*

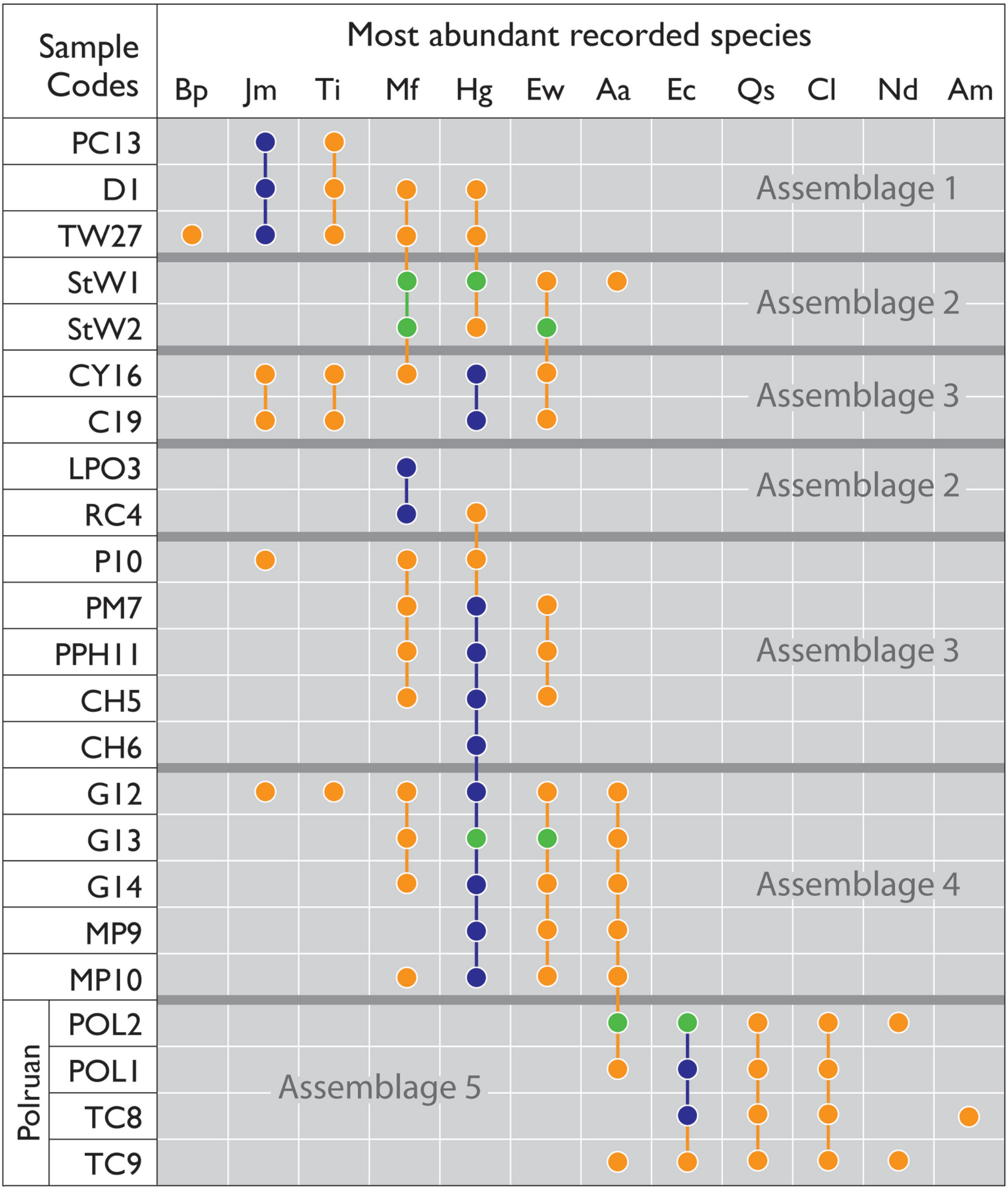

Figure 6. *Distribution of the more important species of foraminifera throughout the estuary showing the dominant species (blue circles), equally important species (green circles) and subordinate species (orange circles). The species listed include* B. pseudomacrescens *(Bp),* J. macrescens *(Jm),* T. inflata *(Ti),* M. fusca *(Mf),* H. germanica *(Hg),* E. williamsoni *(Ew),* Ammonia *sp. cf.* A. aberdoveyensis *(Aa),* E. crispum *(Ec),* Q. seminulum *(Qs),* C. lobatulus *(Cl),* Nonion depressulus *(Nd) and* A. mamilla *(Am).*

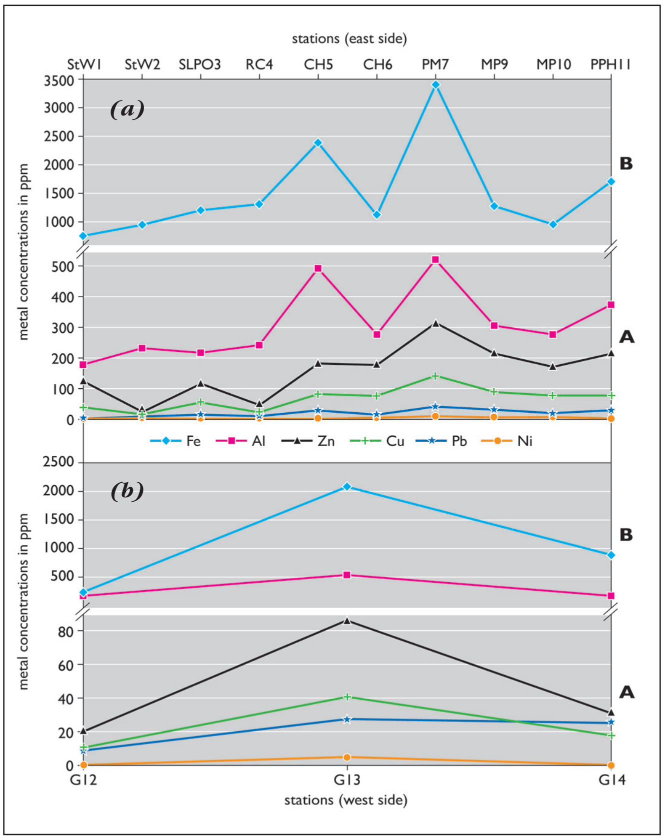

Figure 7. *Distribution of sediment-bound metals in the Fowey Estuary. (**a**) The East side of the estuary, with separate graphs of (**A**) Ni, Pb, Cu, Zn and Al; (**B**) Fe, and (**b**) the West side of the estuary, with separate graphs of (**A**) Ni, Pb, Cu and Zn; (**B**) Fe and Al.*

Deformed foraminifera

Stubbles (1999) used the Fowey Estuary as an example of a non-polluted environment in order to make comparisons with her data from Restronguet Creek (Stubbles, 1993; Stubbles *et al.*, 1996). She concluded, at that time, that the Fowey Estuary was polluted by 'natural' mine-derived waters and did record a significant number of deformed foraminifera (in comparison to the River Erme in Devon). The distribution of deformed foraminifera recorded by Stubbles (1999, figure 5.25) shows a maximum value of 5% of the standing crop (summer at CH5 and spring at G12). The majority of sample locations recorded values between 1% and 3% of the assemblage, and this is also the case in samples collected in 2013/2014.

There is considerable interest in the cause(s) of test deformity in foraminifera, beginning with the work of Carpenter (1856). Alve (1995, pp. 196-197) reviewed the known causes of test deformity (e.g. abnormal salinity, reduced nutrition levels, pollution, rapidly changing environmental conditions, etc.) as well as the occurrence of malformed tests in geological samples (e.g. Caralp, 1989). While deformed tests are relatively rare in the fossil record, there are some stratigraphical horizons (e.g. Christian Malford Squid Bed, Callovian, Jurassic) where there are unusual assemblages that include a high percentage of deformed specimens. In the 1990s there was an increasing interest on the potential use of foraminifera as pollution indicators. Yanko *et al.* (1994, 1998) indicated that the deformities, potentially caused by pollution, included disrupted coiling, aberrant chamber shape and size, multiple apertures, irregular keels and a lack of ornamentation. The Wheal Jane pollution incident in Cornwall provided an interesting test of the pollution/deformity debate and was investigated by Stubbles (1993, 1995, 1999), Stubbles *et al.* (1996) and Olugbode *et al.* (2005). In the post-Wheal Jane period (1992-1995) the percentages of deformed individuals in the standing crop varied from 1.5% to 22.5%, including a fairly consistent level of 6.0% to 19.0% for early 1993 to mid-1995 at Tallack's Creek (east of Devoran) in Restronguet Creek. In the Fowey Estuary, Stubbles (1999) showed that deformity was only seen in the tests of *H. germanica* and *E. williamsoni*, with no records of agglutinated taxa being affected. In more recent sampling it has been found that some specimens of *J. macrescens* have irregular test construction (Figure 4, (8), (9)) though most of the species with deformities are those with calcareous tests (Figure 5 (14)). While the specimen of *C. lobatulus* in Figure 5 (10) looks slightly deformed, this species is not counted within the totals of deformed individuals as its epifaunal/epiphytal life style often leads to slightly irregular chamber arrangements. The maximum percentage of deformed individuals (4% of standing crop) was recorded in samples from PM7, where there is a right-to-discharge permission. All the other samples recorded figures between 1% and 2.2% of the standing crop.

Stubbles (1999, pp. 252-257) and Stubbles *et al.* (1996) reported the use of laser ablation ICP-MS to determine the geochemistry of deformed chambers. While it was not conclusive, the deformed specimens in the Fowey Estuary did show a 'significant' correlation with Zn. The levels of test deformity in the Fowey Estuary are, however, much lower than in Restronguet Creek where levels of Al, Cu and Zn are considerably higher (Table 2). If metal pollution is the cause of test deformity, the data in Table 2 suggest that Al, Cu or Zn may be the cause, although not all elements have been analysed and further work needs to be undertaken.

Summary

The species recorded in the Fowey Estuary are typical of all the other estuaries in the region and the marine assemblage recorded at Polruan is comparable to the assemblages described by Heron-Allen and Earland (1916, 1930), Murray (1965, 1970), Castignetti (1997), Manley (1997), Olugbode *et al.* (2005) and Sadri *et al.* (2011). The distribution of taxa shown in Figure 6 has allowed the identification of 5 distinctive assemblages although the pattern is slightly complicated by the placing of samples from Lerryn, Middle Penpol and Pont Pill into a sequence attempting to plot data along the length of the estuary. The five assemblages are: (1) saltmarsh; (2) higher estuary (1); (3) higher estuary (2); (4) lower estuary; and (5) marine estuary. These, or very similar, sub-environments can be identified in many estuaries in South-West England (e.g. Restronguet Creek, Cornwall); Fal River, Cornwall; Looe River, Cornwall; River Erme, Devon; River Avon, Devon; and Christchurch Harbour, Dorset; see Murray, 1968b). A similar pattern (estuarine to marine) was recorded by Eddles and Hart (1989) and Castignetti (1993) in two boreholes collected from the buried channel of the River Tamar in Plymouth Sound (Eddies and Reynolds, 1988) and which recorded the post-glacial rise in sea level. This pattern has also been recorded (including the *J. macrescens* + *T. inflata* saltmarsh assemblage) in cores between Jersey and France (Consolaro *et al.*, 2014) and which record the rapid Holocene sea level rise in that area.

The occurrence of deformed foraminifera is much less in the Fowey Estuary than that recorded in Restronguet Creek. An analysis of the sediment geochemistry in both estuaries has shown that metal levels in Restronguet Creek are much higher, and that some of the differences may indicate the elements responsible for the deformities. Experimental work, with individual foraminifera in culture, may have to be undertaken in order to determine the real causes of the disruption to chamber formation.

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APPENDIX: TAXONOMIC NOTES ON FORAMINIFERA

The species mentioned in the text are well-known from UK near-shore marine environments and a full taxonomy is not presented. The species are listed in alphabetical (not taxonomic) order. Note that the taxonomic references are not given in the reference list (above).

Ammonia* sp. cf. *A. aberdoveyensis Haynes
Ammonia aberdoveyensis Haynes, 1973, pp. 184-186, pl. 18, fig. 15, text-fig. 38, nos 1-7.

Astacolus* sp. cf. *A. crepidulus (Fichtel and Moll)
Nautilus crepidula Fichtel and Moll, 1798, p. 107, pl. 19, figs g-i.

Astigerinata mamilla (Williamson)
Rotalina mamilla Williamson, 1858, p. 54, pl. 4, figs 109-111.

Balticammina pseuomacrescens Brönnimann, Lutze and Whittaker
Balticammina pseuomacrescens Brönnimann, Lutze and Whittaker, 1989, p. 169, pls 1-3.

Cibicides lobatulus (Walker and Jacob)
Nautilus lobatulus Walker and Jacob, 1798, p. 642, pl. 14, fig. 36.

Eggerelloides scaber (Williamson)
Bulimina scabra Williamson, 1858, p. 65, pl. 5, figs 136, 137.

Elphidium crispum (Linné)
Nautilus crispus Linné, 1758, Vol. 1, p. 709.

Elphidium williamsoni Haynes
Elphidium williamsoni Haynes, 1973, p. 207, pl. 24, fig. 7, pl. 25, figs 6–9, pl. 27, figs 1-3.

Haynesina germanica (Ehrenberg)
Nonionina germanica Ehrenberg, 1840, p. 23; figure in Ehrenberg, 1841, pl. 2, fig.1a-b.

Jadammina macrescens (Brady)
Trochammina inflata (Montagu) var. *macrescens* Brady, 1870, pp. 290-291, pl. 11, figs 5a-c.

Lagena* sp cf. *L. substriata Williamson
Lagena substriata Williamson, 1848, p. 15, pl. 2, fig. 12.

Miliammina fusca (Brady)
Miliammina fusca Brady, 1870, pp. 286-287, pl. 11, figs 2a-c, 3a-b.

Quninqueloculina bicornis (Walker and Jacob)
Serpula bicornis Walker and Jacob, 1798, p. 633, pl. 14, fig. 2.

Quinqueloculina cliarensis (Heron-Allen and Earland)
Miliolina cliarensis Heron-Allen and Earland, 1930, p. 58, pl. 3, figs 26-31.

Quinqueloculina* sp. cf. *Q. lata Terquem
Quinqueloculina sp. cf. *Q. lata* Terquem, 1876, p. 82, pl. 11, fig. 8a-c.

Quinqueloculina oblonga (Montagu)
Vermiculum oblongum Montagu, 1803, p. 522, pl. 14, fig. 9.

Quinqueloculina seminulum (Linné)
Quninqueloculina seminulum Linné, 1758, vol. 1, p. 786.

Spiroloculina* sp. cf. *S. rotunda d'Orbigny
Spiroloculina sp. cf. *S. rotunda* d'Orbigny, 1826, p. 299.

Trochammina inflata (Montagu)
Nautilus inflatus Montagu, 1808, p. 81, pl. 18, fig. 3.