The Distribution of Foraminifera in the Fal Estuary (Cornwall)

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The Fal Estuary (Cornwall) is a part of the Fal and Helford Special Area of Conservation (SAC). It contains a nationally important accumulation of calcareous red seaweeds commonly referred to as maerl. Maerl beds are often associated with high benthic diversity but there has been little research done on the associated microfossil assemblages. This investigation has studied the foraminifera that are found within samples that contain maerl as well as the other sediments in the estuary. Samples from the Truro, Tresillian, Fal and Percuil rivers, coupled with samples from Restronguet and Calenick creeks, have been supplemented by over 50 samples collected from the marine part of the estuary in autumn 2016. Foraminifera from the whole of the Fal Estuary are typical of saltmarsh, estuarine and near-shore marine assemblages reported elsewhere in South-West England, including diverse, and variable, assemblages of *Ammonia* spp. This genus, though abundant in many estuarine and near-shore marine assemblages, has a complicated taxonomy and remains a problem for many micropalaeontologists. Despite rDNA and morphometric analysis identification of the various 'species' is so difficult that consistency is a problem. In the Fal Estuary and adjacent marine areas un-ornamented to highly ornamented forms are present, often in the same samples.

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Introduction

Under the Habitats Directive of the European Union (Natura 2000), a number of areas have been designated as Special Areas of Conservation (SAC). One such area is the 6387.8 ha of the Fal and Helford SAC which encompasses the Helford River, part of Falmouth Bay and the Fal Estuary (Figure 1). This area includes sea inlets, tidal rivers, estuaries, mud flats, sand flats, salt marsh, salt pasture, sand dunes, beaches, machair, cliffs and islets. This SAC is one of the most important ria (drowned valley) systems in South-West England, with a central, sinuous, relatively deep (20–30 m) channel (Sheehan *et al.*, 2015). The low fresh water input from a number of small rivers (e.g., Carnon, Fal, Percuil, Tresillian, Truro, etc.) has allowed the development of a range of fully marine habitats from the extremely sheltered to the wave-exposed, tide-swept open coastline. Of particular importance are the maerl beds that are found on St Mawes Bank and extensive areas of maerl 'gravel' (Sheehan *et al.*, 2015) which extend within an area of the Carrick Roads, Falmouth Bank and Falmouth Bay (Hart *et al.*, 2015, fig. 2). These are the largest known maerl beds in South-West England and they provide habitat for an extremely high diversity of algae and a great many infaunal and epifaunal species (Bosence and Wilson, 2003; Peña *et al.*, 2014; Hart *et al.*, 2015). Maerl is the collective name for a number of species of red seaweeds (Rhodophyta) that develop hard, calcareous skeletons (Corallinaceae). Maerl forms twig-like, branching forms and, as the living alga, requires sunlight to grow, occupies shallow water areas within the open marine part of the SAC. The maerl in the Fal Estuary is composed of two species: *Phymatolithon calcareum* (Pallas) and *Lithothamnion corallioides* (P. & H. Crouan) and has been described by Bosence (1976), Farnham and Bishop (1985), Irvine and Chamberlain (1994), Birkett *et al.* (1998) and Hall-Spencer *et al.* (2010). Beds of maerl are concentrated along the western coastline of Europe in the NE Atlantic Ocean (Peña *et al.*, 2014, fig. 1; Dutertre *et al.*, 2015), including SW England, Brittany, Western Ireland, the Inner Hebrides and Iceland. The maerl was dredged for agricultural use until 2005, when the Board of Falmouth Harbour Commissioners ceased to licence its extraction, following UK Government advice from English Nature and the Department for the Environment, Fisheries and Rural Affairs (Defra): see Hall-Spencer (2005).

Material and Methods

Aside from the samples of maerl from the Fal Estuary (see Sheehan *et al.*, 2015), a number of other samples have been collected from the headwaters of the Tresillian River near Pencalenick (SW 860454), Fal River near Lamorran (SW 877417), Percuil River near Trethem Mill (SW 862363), Calenick Creek east of Calenick (SW 827432), Tallack's Creek east of Devoran (SW 802389), and in a boatyard near St Just-in-Roseland (SW 847357). These are in addition to the extensive sampling of Restronguet Creek over the past 20+ years, and described by Stubbles (1993, 1999), Olugbode *et al.* (2005) and

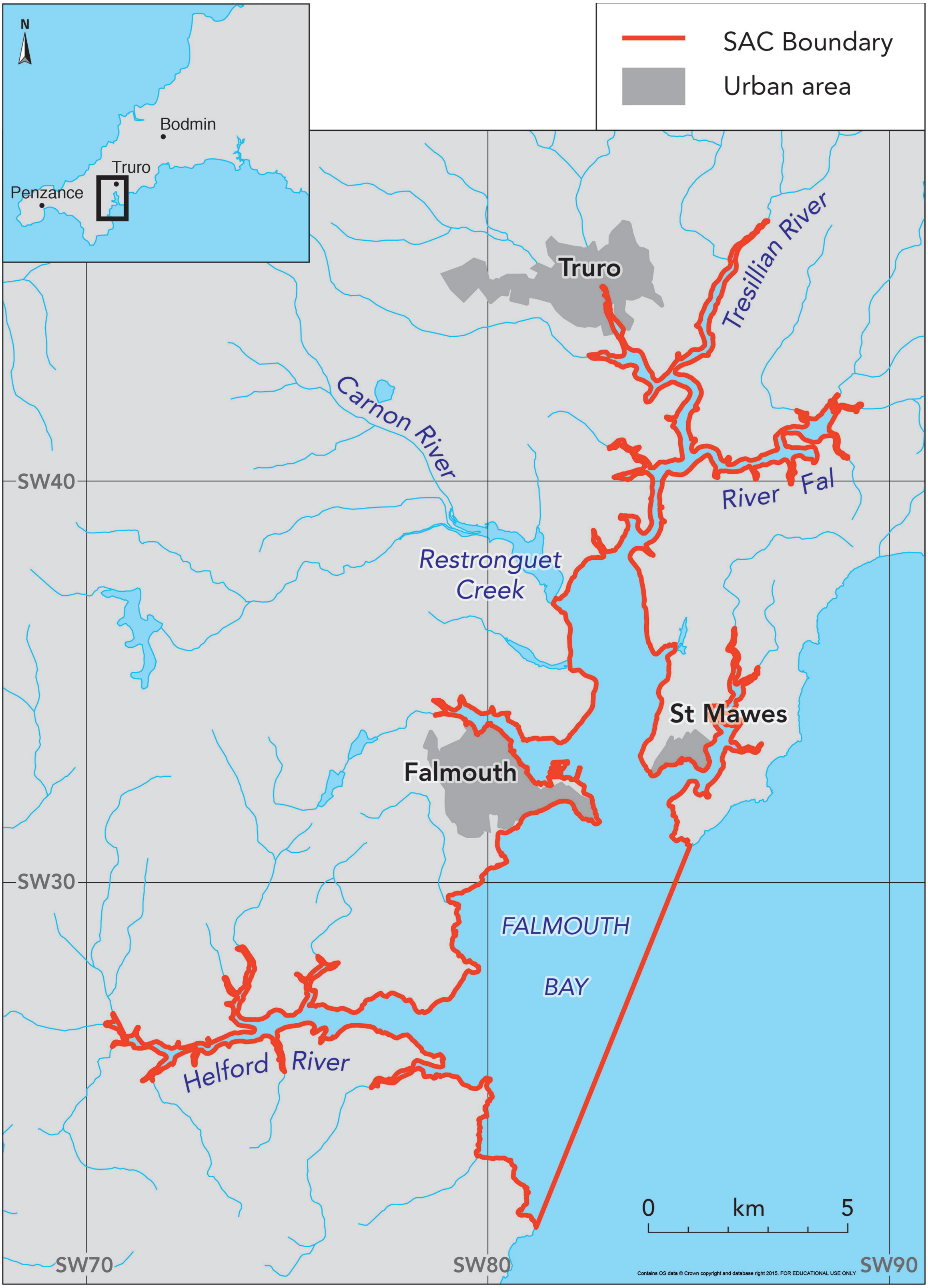

Figure 1. *The boundaries of the Fal and Helford Special Area of Conservation (after Hart* et al. *(2015).*

Hart *et al*. (2015). In 2016, Dr Matt Witt and his students from the Centre for Ecology and Conservation (Exeter University, Penryn Campus) collected 100+ samples from the Fal Estuary and some of these samples have been used in this present work (Figure 2). This has provided a comprehensive suite of marine grab samples from the more open areas of the Fal Estuary. Most of the samples collected in the Fal Estuary system were stored directly in buffered formalin (10%), having been taken from the uppermost 1 cm of the inter-tidal sediments enclosed in a 10 cm diameter ring (Hart *et al*., 2015, figure 4a). All samples have been washed on a 63 μm large diameter sieve to remove the fine sediment. Sieved residues were then placed in rose Bengal organic stain (1 g per litre de-ionized water) for three hours before being re-washed on the 63 μm large diameter sieve. Once the water ran clear of mud and stain, the samples were filtered and dried in a cool oven (<40°C). Dried residues were studied in a range of size fractions (>500 μm, 500–250 μm, 250–150 μm and 150–63 μm). Images of the foraminifera and other microfauna/microflora were generated using a JEOL 6600LV or a JEOL 7100FE Field Emission scanning electron microscope.

The maerl present in some of the samples was inspected at low magnification in order to determine if any epifauna was present. Serpulid worms, some of which were quite small, were frequently encountered but no adherent foraminifera were found. Even after quite vigorous washing, however, some foraminifera were still found in the interstices of the maerl, but these were not thought to be adherent forms.

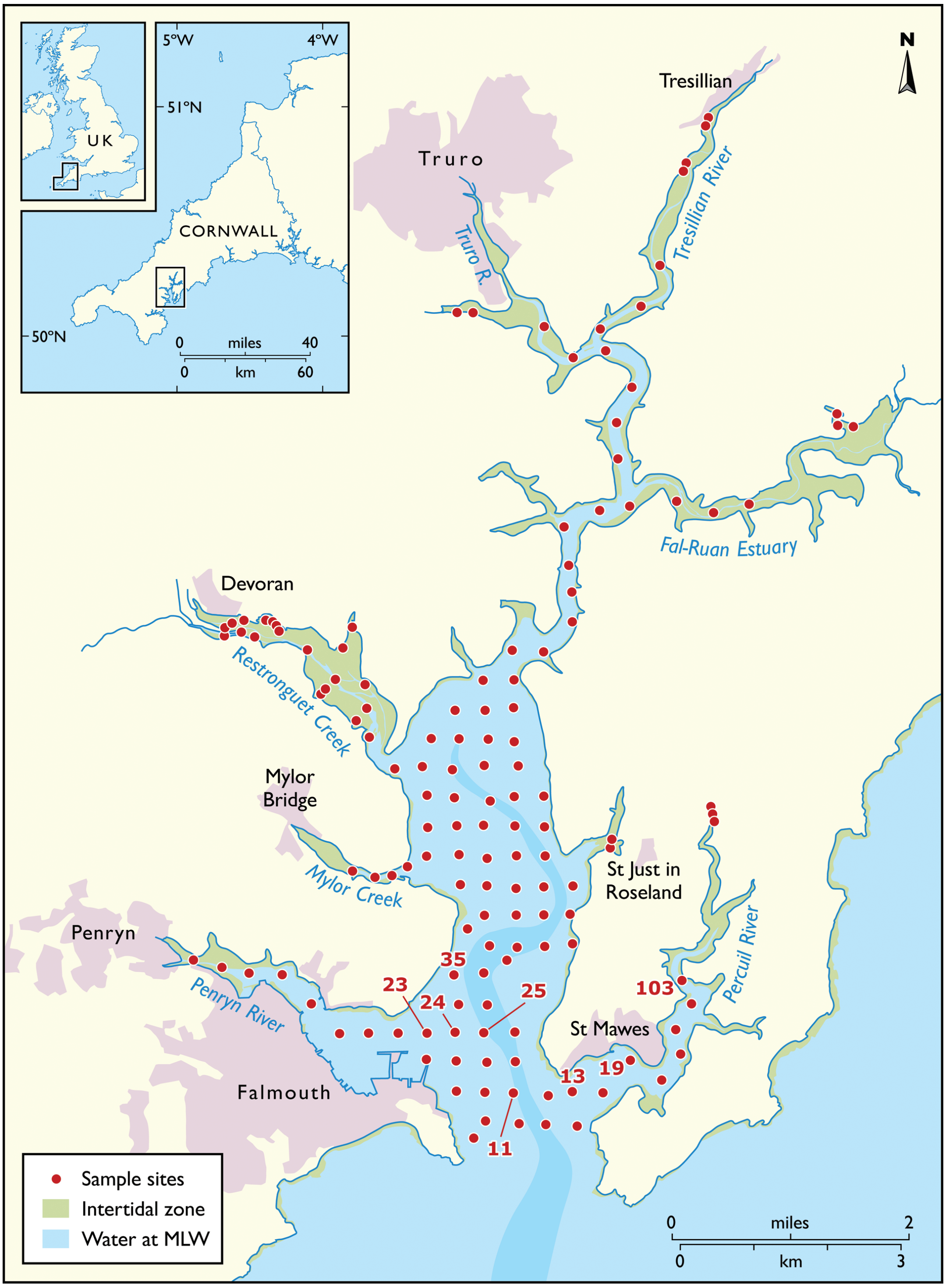

Figure 2. *Distribution of samples studied from the Fal Estuary and its associated creeks and rivers. The numbered sites are those that appear in Table 1.*

Foraminifera

Foraminifera are single-celled protists that are known to live in both marine and estuarine environments. They can tolerate both hypersaline as well as hyposaline environments and are, therefore, found in low salinity and salt marsh environments. The marine and coastal waters of South-West England have been studied by micropalaeontologists for over 200 years and this region has provided a significant contribution to our knowledge of shallow-water species. The early work by Montagu (1803, 1808), who lived in Kingsbridge (Waterhouse, 2014), has been followed by Millett (1885), Heron-Allen and Earland, 1930; Murray (1965a, 1970, 1971), Stubbles (1993, 1999), Castignetti (1997), Olugbode *et al*. (2005) and Hart *et al*. (2014, 2015, 2017). Foraminifera from the Fal Estuary have been illustrated by Hart *et al*. (2015, fig. 5), in addition to those illustrated from the Fowey Estuary (Hart *et al*. (2014, figs 4, 5) and – more recently – offshore Plymouth (Hart *et al*., 2017, fig. 4). In the study of the Fowey Estuary, Hart *et al*. (2014, fig. 6) identified five assemblages, each characterized by the dominance of one species or the co-dominance of two species. Comparable assemblages can also be identified for the sample locations around the Fal Estuary. As all the surface samples collected from the exposed mudflats were located in the upper estuary areas of the tributaries feeding Carrick Roads and the Fal Estuary, it was expected that the majority of samples would yield Assemblages 2 and 3, with Calenick Creek and Tallack's Creek providing the closest assemblages to the salt marsh environment seen at Shirehall Moor near Lostwithiel (Assemblage 1).

The distribution of foraminifera in much of the Fal Estuary is directly comparable to that described in the Fowey Estuary, which is located only 30 km to the east of the Fal Estuary. The Fal Estuary is, however, draining a much larger catchment, which was extensively mined in the nineteenth century (Pirrie *et al*., 2003). In 1991, the Carnon River, Restronguet Creek and Carrick Roads suffered a major flood of acidic mine water from the former Wheal Jane Mine (Stubbles *et al*., 1996) which caused a significant loss of biota (especially in Restronguet Creek). This was the primary reason for the exclusion of Restronguet Creek from the SAC (as shown in Fig. 1), as concentrations of heavy metals are still present within the estuarine sediments (Pirrie *et al*., 2003) despite a natural cleaning and water filtration process being installed at Wheal Jane and in the valley of the Carnon River. This metal pollution is, however, still creating deformities in some species collected from Restronguet Creek (see below).

Saltmarsh environments

True saltmarsh environments are rare in the tributaries of the Fal Estuary, being restricted to small areas at the head of the Fal near Ruan Lanihorne, at the head of Calenick Creek and near Tallack's Creek which is a part of Restronguet Creek near Devoran. Only in Tallack's Creek is an Assemblage 1 association of *Jadammina macrescens* and *Trochammina inflata* found, although *Miliammina fusca* is dominant in Calenick Creek and samples from the higher reaches of the Tresillian River near the A390 road west of Tresillian village. *Miliammina fusca* is also the dominant species found at Trethem Mill at the tidal limit of the Percuil River, although *Haynesina germanica* and *Elphidium williamsoni* are the dominant species in the Tresillian River, Fal River (at Lamorran) and the higher mud flat samples collected in Tallacks' Creek (Restronguet Creek).

Higher mud flats

Since the recovery from the Wheal Jane pollution inclident in 1991 (Stubbles, 1993, 1999; Olugbode *et al*., 2005), Restronguet Creek has been dominated by *E. williamsoni, H. germanica* and *Ammonia* sp. cf. *A. aberdoveyensis* and the Tallack's Creek samples confirmed that this is still the case. *E. williamsoni* and *H. germanica* also dominated the boatyard sample at St Just-in-Roseland, although this location also recorded more normal marine species (*Quinqueloculina* spp., *Cibicides lobatulus*, and *Reophax moniliformis*). The St Just-in-Roseland sample is, therefore, comparable to Assemblage 4 of the Fowey Estuary and, especially, the samples from the boatyard area near Golant.

Entrance to Percuil River near St Mawes

The marine area immediately off-shore St Mawes contains a small sea grass meadow, as well as sediments in which there are transported maerl fragments. The samples from this area (Fig. 2) have formed a pilot study for a wider assessment of the Fal Estuary system (Table 1). The assemblage of foraminifera is diverse with many of the samples containing ~30 species. In all the samples the dominant taxa are *Elphidium crispum, Cibicides lobatulus* and *Astigerinata mamilla*. All of these are typical marine taxa, with *E. crispum* being particularly associated with sea grass meadows (Sadri *et al*., 2011), as are *Cibicides lobatulus* and *Lamarckina haliotidea*. Agglutinated taxa are relatively rare, and this is a normal feature of the open marine parts of estuaries in S. W. England.

Maerl samples

The main area of living maerl, offshore St Mawes Castle, has not been sampled as it is an highly fragile ecosystem. Sheehan *et al*. (2015) were specifically licensed to collect maerl samples near Falmouth Docks, which includes a mixture of dead maerl with only scattered patches of living maerl. Samples collected by the Centre for Ecology and Conservation (Fig. 2), also included material from areas close to Falmouth Docks, but many other samples from Carrick Roads contained what is presumed to be transported maerl.

The assemblages from the maerl samples were, as expected, quite different in being dominated by *Elphidium crispum, Astigerinata mamilla, Quinqueloculina* spp. and *Rosalina globularis*. The maerl-rich samples also included a mixture of some rare saltmarsh taxa (e.g., *J. macrescens*), estuarine species (e.g., *H. germanica, E. williamsoni*) and many open marine species (e.g., *Ammonia batava, Trochammina ochracea, Cribrostomoides jeffreysii, Astigerinata mamilla, Fissurina* sp., *Parafissurina* spp., *Oolina* spp. *Quinqueloculina cliarensis, Q. bicornis, Brizalina* sp., *Globocassidulina* sp., and the normally very rare *Sejunctella earlandi*). The most common foraminifera in the counted material is *E. crispum* (30.5%), closely followed by *A. mamilla* (26%). In a comparable count of a maerl sample from Stravanan Bay, Isle of Bute (Scotland), Austin and Cage (2010) give figures for *A. mamilla* (16.5%), *E. crispum* (1.5%) and *A. batavus* (1%) that look quite different from the samples collected in the Fal Estuary. Sadri *et al*. (2011) recorded high numbers of living *E. crispum* on the fronds of sea grass (*Zostera marina*) in Tor Bay during the summer months. The data from Tor Bay suggest that, in the autumn months, when the maerl-rich samples from the Fal Estuary were collected, specimens of *E. crispum* that had been living in association with the nearby sea grass meadows during the summer had been transported into the area of the maerl and become trapped with an assemblage of other marine and estuarine taxa.

The Genus *Ammonia*

One of the most intractable problems facing those working on near-shore foraminifera is the identification of 'species' of the genus *Ammonia* (Figs 3, 4). Many of these 'species' date back to the eighteenth and nineteenth centuries, with problems that relate to the quality of the initial figures and the definitions of the taxa. In much of the twentieth-century literature specimens were often recorded as *Ammonia beccarii* (Linnaeus, 1758), with the original type locality given as Rimini Beach (Adriatic Sea), Italy: see Hofker (1951), Cifelli (1962),

Species	11	13	24	23	25	35	19	103
Ammonia spp.	18	3	3	9	12	13	86	1
Elphidium crispum	227	110	109	196	164	262	157	46
Elphidium gerthi	3	7	0	0	2	0	2	16
Elphidium earlandi	0	1	0	0	1	0	0	0
Elphidium articulatum	3	21	0	0	8	0	2	26
Lenticulina orbicularis	4	0	1	0	0	4	0	0
Lenticulina sp.	0	0	0	3	1	0	0	0
Massilina secans	5	5	0	0	0	0	0	0
Quinqueloculina spp.	118	35	78	127	177	162	69	0
Cibicides lobatulus	39	193	13	7	9	14	166	13
Cibicides pseudoungerianus	0	0	0	1	0	0	0	0
Globulina gibba	3	1	1	0	1	1	1	0
Vaginulina subelegans	1	0	0	0	0	0	0	0
Vaginulina spp.	0	0	0	0	1	6	0	0
Dentalina sp.	0	0	0	0	1	0	0	0
Bolivina variablis	2	0	0	0	1	0	0	0
Spiroloculina rotunda	0	0	0	0	1	0	0	0
Spiroloculina excatava	3	1	0	1	1	2	0	0
Spirillina wrightii	11	0	0	0	0	0	0	0
Spirilina vivipara	0	8	0	0	4	1	0	0
Rotorbinella rosea	19	3	7	41	0	34	0	0
Glabratella millettii	5	5	2	13	18	1	0	1
Discorbis cf. *D. wrightii*	0	4	0	0	0	0	0	0
Textularia sagittula	14	15	1	3	11	0	0	0
Gaudryina rudis	0	0	0	0	1	0	0	0
Rosalina bradyi	10	34	0	5	19	0	2	0
Rosalina williamsoni	0	0	0	0	0	1	1	0
Rosalina globularis	8	1	0	0	3	1	3	0
Asterigerinata mamilla	151	23	28	150	64	96	3	2
Patellina corrugata	8	0	0	0	0	2	0	0
Oolina saquamosa	1	0	0	0	3	0	0	0
Oolina globosa	0	0	0	1	0	0	0	0
Oolina hexagona	0	0	0	0	0	1	0	0
Oolina sp.	0	0	0	0	0	0	0	1
Miliolinella subrotunda	3	15	2	7	0	0	1	0
Milionella circularis	1	1	0	0	0	0	0	0
Fissurina orbignyana	1	4	1	1	4	0	0	0
Fissurina quadrata	0	0	0	0	1	0	0	0
Fissurina lucida	0	0	0	0	0	0	1	1
Fissurina cf. *lucida*	0	0	0	0	1	0	0	0
Parafissurina malcomsoni	2	0	0	0	0	0	0	0
Astacolus crepidulus	1	0	0	0	1	1	0	0
Eggerella scabra	0	6	0	1	2	0	4	1
Ammoscalaria runiana	0	1	0	0	0	0	0	1
Triloculina cf. trihedra	0	10	0	0	0	0	0	0
Triloculina trihedra	3	0	0	3	0	0	0	0
Globocassidulina sp.	0	1	0	0	0	0	0	0
Lagena perlucida	0	1	0	0	0	0	0	0
Bulimina elongata	0	1	0	0	1	1	1	1
Bulimina marginata	1	0	0	0	1	0	0	1
Brizalina variabilis	0	3	0	0	0	0	0	0
Haynesina orbicularis	0	1	0	0	2	0	6	41
Haynesina depressulus	0	0	0	0	0	0	1	7
Haynesina germanica	0	0	0	0	0	0	1	21
Spiroplectinella wrightii	0	0	1	0	0	0	0	0
Planulina sp.	0	0	1	1	4	0	0	0
Cibrostomoides jeffreysii	0	0	0	2	1	1	0	3
Tritaxis fusca	0	0	0	1	0	0	0	0
Adelosina sp.	0	0	0	2	3	0	0	0
Nodosaria sp.	0	0	0	2	0	0	0	0
Eponides repandus	0	0	0	0	2	2	0	0
Trifarina angulosa	0	0	0	0	2	0	0	0
Trochammina sp. cf. *T. ochracea*	0	1	0	0	0	0	0	0
Lamarckina haliotidea	0	1	0	2	0	0	0	0
Turrispirillina sp.	0	0	1	0	0	0	0	0
Ammobaculites balkwilli	0	0	0	0	0	0	0	1
Jadammina macrescens	0	0	0	1	0	0	0	0
TOTAL	665	514	248	577	528	606	507	183

Calcareous
Agglutinated
Porcellaneous

Table 1. *Distribution of foraminifera at sites 11, 13, 19, 23, 24, 25, 35 and 103.These sites are indicated in Figure 2.*

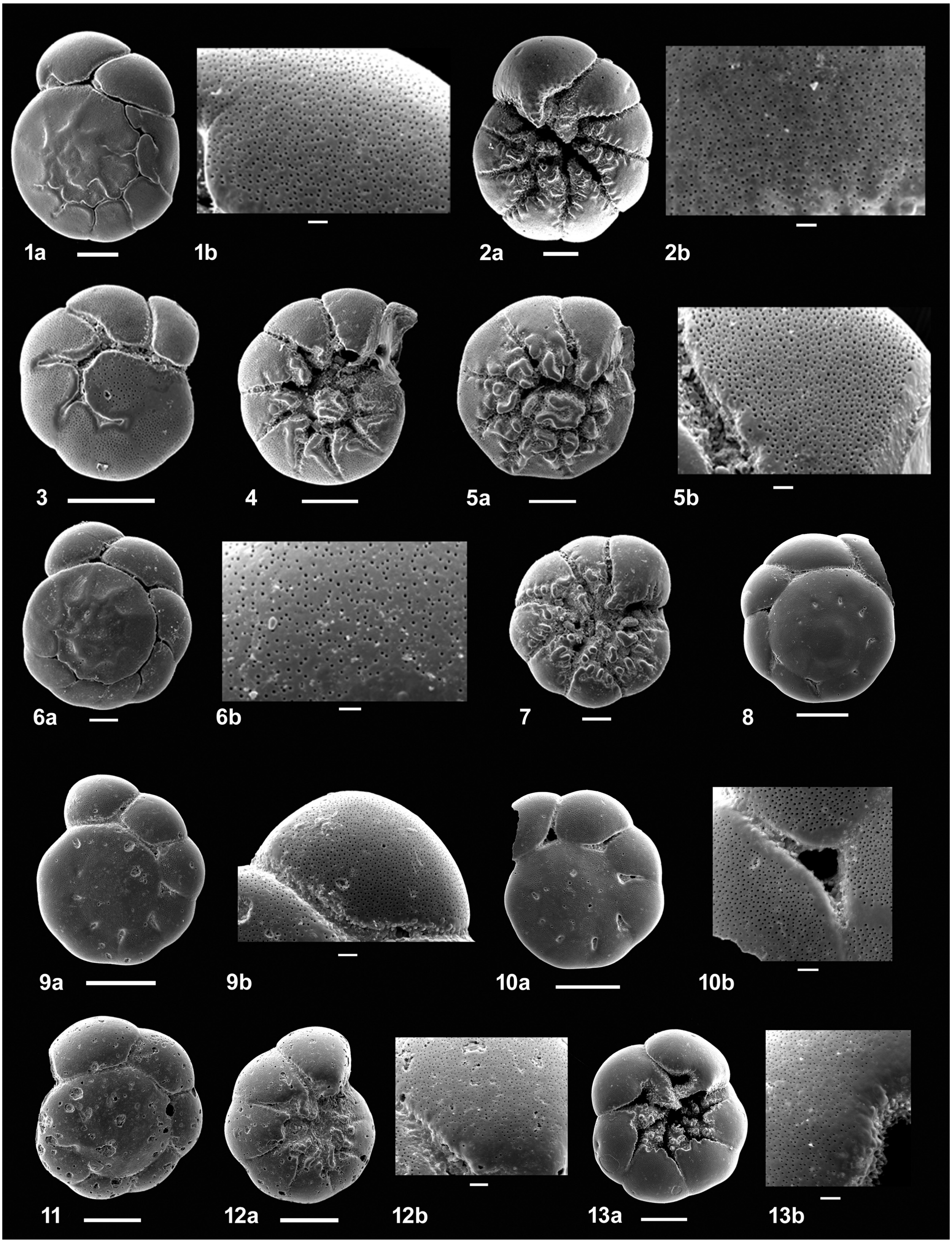

Figure 3. *Scanning electron micrographs of* Ammonia *spp. The scale bar length is indicated.*
1a. Ammonia batava, *spiral side,100 µm, L4 surface sediment;* ***1b***. Ammonia batava, *spiral side, final chamber, 10 µm, L4 surface sediment;* ***2a***. *Ammonia. batava umbilical side 100 µm, L4 surface sediment;* ***2b***. Ammonia batava, *umbilical side, 10 µm L4 surface sediment;* ***3***. Ammonia batava, *spiral side,100 µm, L4 surface sediment;* ***4***. Ammonia batava, *umbilical side, 100 µm, L4 surface sediment;* ***5a***. Ammonia batava, *umbilical side, 100 µm, L4 surface sediment;* ***5b***. Ammonia batava, *umbilical side, final chamber, 10 µm, L4 surface sediment;* ***6a***. *Ammonia batava, spiral side, 100 µm, off-shore Jersey, sample containing maerl;* ***6b***. Ammonia batava, *10 µm, off-shore Jersey, sample containing maerl;* ***7***. Ammonia batava, *umbilical side, 100 µm, off-shore Jersey, sample containing maerl;* ***8***. Ammonia falsobeccarii, *spiral side, 100 µm, Station L4;* ***9a***. Ammonia falsobeccarii, *spiral side, 100 µm, Station L4;* ***9b***. Ammonia falsobeccarii, *10 µm, Station L4;* ***10a***. Ammonia falsobeccarii, *spiral side, 100 µm, Station L4;* ***10b***. Ammonia falsobeccarii, *10 µm, final chamber, Station L4;* ***11***. Ammonia tepida, *spiral side, 100 µm, Station L4;* ***12a***. Ammonia tepida, *umbilical side, 100 µm, Station L4;* ***12b***. Ammonia tepida, *10 µm, Station L4;* ***13a***. Ammonia tepida, *umbilical side, 100 µm, Station L4;* ***13b***. Ammonia tepida, *10 µm, final chamber, Station L4.*

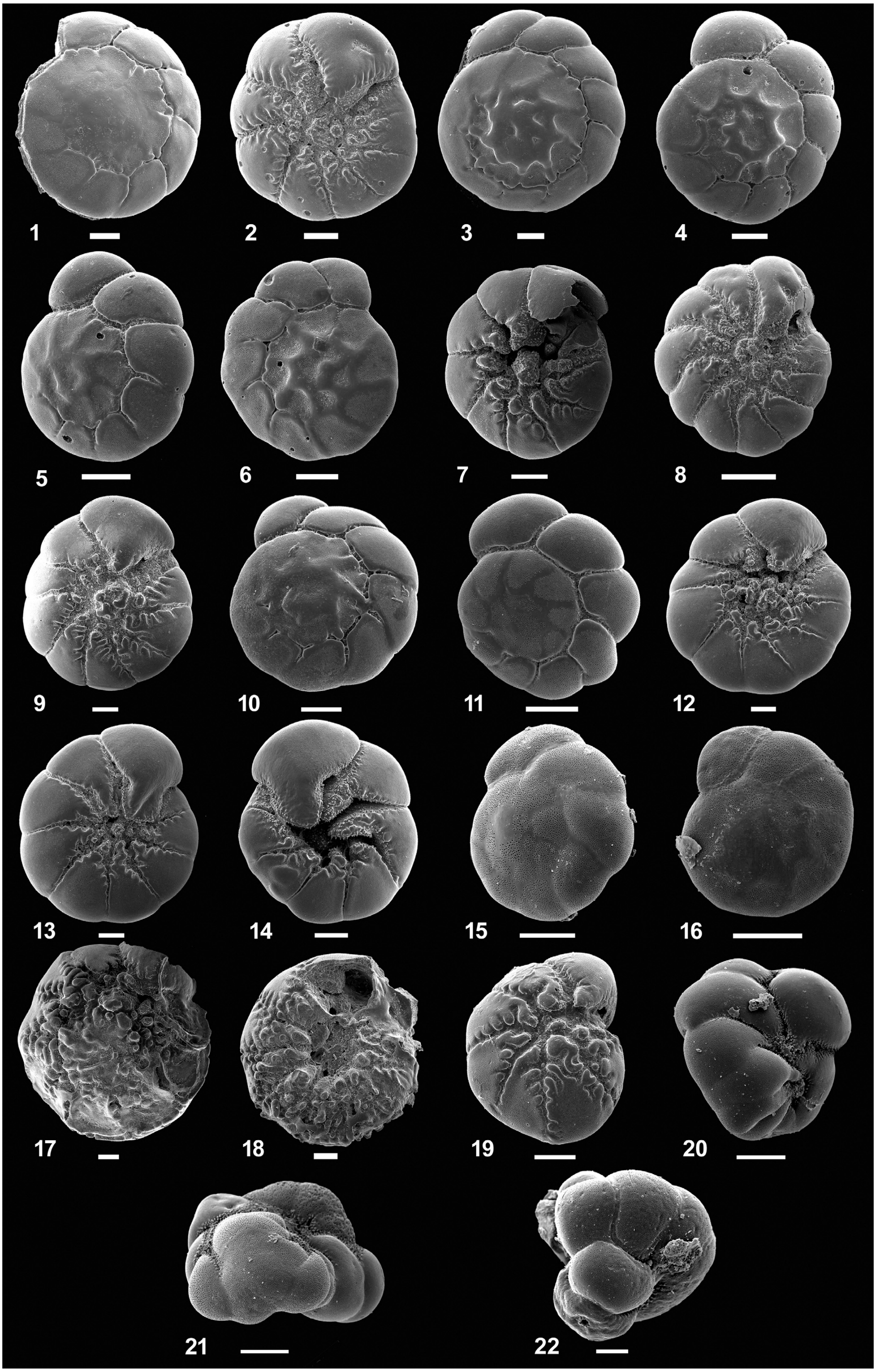

Figure 4. *Scanning electron micrographs of* Ammonia *spp. In all cases the scale bar represents 100 μm.*
1. Ammonia batava, *spiral side, off-shore St Mawes, Fal Estuary;* ***2***. Ammonia batava, *umbilical side, off-shore St Mawes, Fal Estuary;* ***3–6***. Ammonia falsobeccarii, *spiral side, off-shore St Mawes, Fal Estuary;* ***7–9***. Ammonia falsobeccarii, *umbilical side, off-shore St Mawes, Fal Estuary;* ***10–11***. Ammonia tepida, *spiral side, off-shore St Mawes, Fal Estuary;* ***12–14***. Ammonia tepida, *umbilical side, off-shore St Mawes, Fal Estuary;* ***15–16***. Ammonia *sp. cf.* A. aberdoveyensis, *spiral side, Restronguet Creek;* ***17–19***. Ammonia *sp. umbilical side, Restronguet Creek;* ***20–22***. *Deformed* Ammonia *sp. cf.* A. aberdoveyensis, *Restronguet Creek, surface sediment between Devoran and Penpol.*

Walton and Sloan (1990) and Hayward *et al.* (2004, pp. 262–263).

There are now more than 40 species, sub-species (or varieties) and morphotypes of *Ammonia* that have been described from Recent sediments worldwide, many of which come from a range of highly variable, near-shore environments. Some authors have adopted a 'traditional' taxonomic approach and continue to use formally defined names (e.g., Cimerman and Langer, 1991) while others have abandoned this approach (e.g., Poag, 1978 and Jorissen, 1988). More recently, Langer (2000, 2001) in a study of *Haynesina germanica* and Hayward *et al.* (2004) in a study of the genus *Ammonia* have adopted a molecular approach (rDNA) alongside a morphometric approach to the determination of species. Specimens from Plymouth Sound, provided by Dr Catherine Manley, were incorporated into the analysis by Hayward *et al.* (2004) and it could be assumed that taxa recorded along the English Channel coast might be regarded as a single population, although Hayward *et al.* (2004, pp. 267–268) indicate that more than one form can be present in a single sample (especially where there may be some post-mortem transport of empty tests in dynamic near-shore environments). The living material from Plymouth Sound, which came from muddy sediments immediately inshore of the Breakwater (Fig. 5), clustered into molecular types T3 and T2. In the latter grouping (T2), it may be significant that others in this cluster came from Cape Cod and Aberdovey (Wales). The Dovey Estuary was the location for a major study of foraminifera from both that estuary and the wider region of Cardigan Bay undertaken by Haynes (1973). It is quite significant that the location of the type material of *Ammonia aberdoveyensis* was the Dovey Marshes and that this relatively un-ornamented 'species' was, therefore, from a

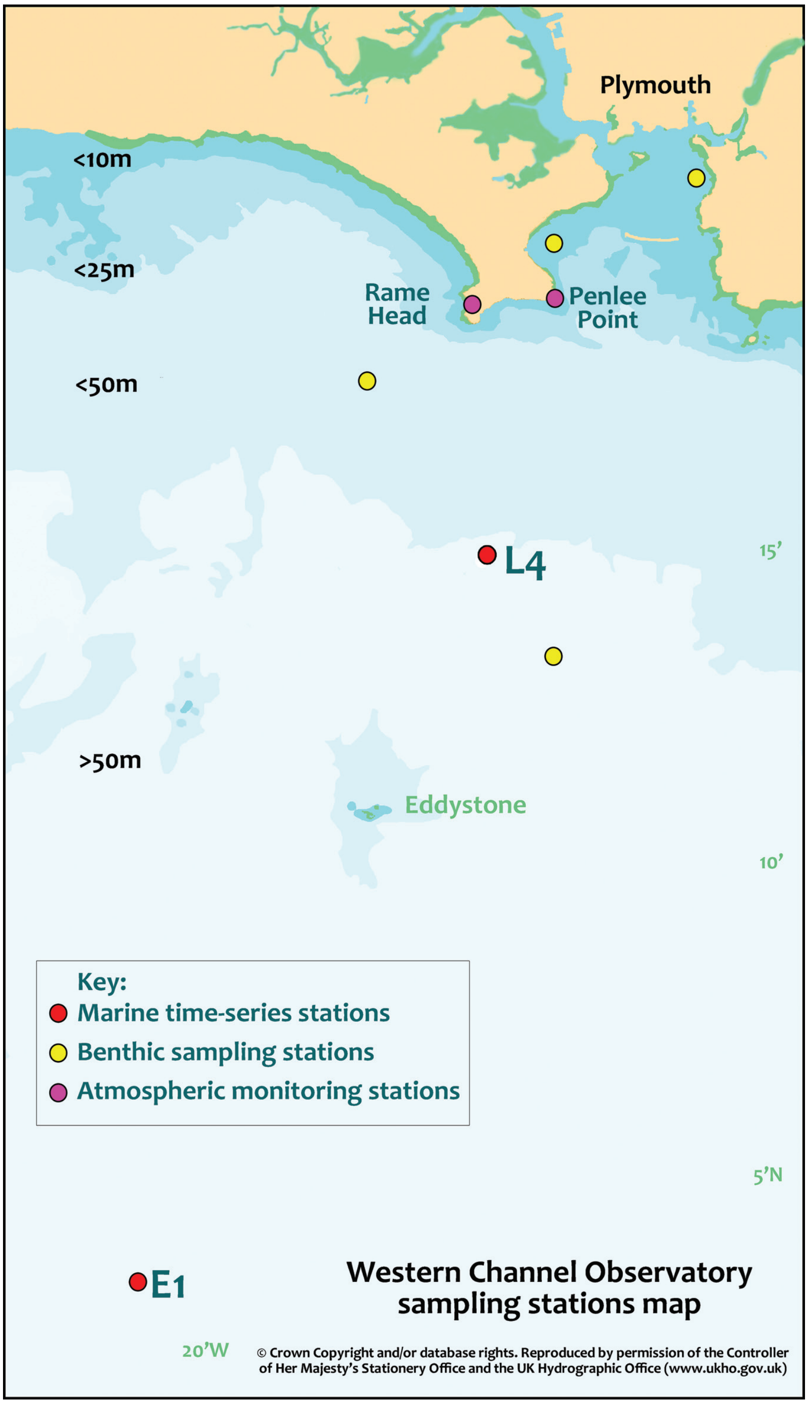

Figure 5. *. Map of the marine area adjacent to Plymouth showing the Stations (L4, E1, Cawsand, etc.) used by the Western Channel Observatory (see Hart* et al.*, 2016, fig. 1). Hillsand, another benthic sampling station is located immediately SSE of L4. The samples of* Ammonia *provided rDNA analysis came from a location immediately inshore of the centre of the Plymouth Breakwater.*

brackish water, low carbonate saturation (ΩCarbonate) environment. The holotype of the 'species' appears to be a microspheric form with none of the tubercles, bosses, or other ornamentation shown by many specimens attributed to *Ammonia* (Figs 3, 4). As a result of this determination by Haynes (1973) and the molecular work of Hayward *et al.* (2004), Olugbode *et al.* (2005) used *Ammonia* sp. cf. *A. aberdoveyensis* for the *Ammonia* specimens found in Restronguet Creek (Fig. 4; 15, 16, 20–22). In this off-shoot of the Fal Estuary, near Devoran and Penpol, specimens of *Ammonia* sp. cf. *A. aberdoveyensis, Haynesina germanica* and *Elphidium williamsoni* are often deformed (Olugbode *et al*., 2005). While some of these deformities often affect the later chambers and primary apertures, some individuals are 'extremely' deformed (Fig. 4; 20–22). This probably indicates that the metal pollution in the sediments, enhanced by the Wheal Jane mine water incident in 1992, still remains available to the biota (Stubbles 1993, 1999; Stubbles *et al*., 1996; Pirrie *et al*., 2003; Olugbode *et al*., 2005).

Specimens of *Ammonia* spp. collected from the Fal Estuary have been compared to those from the Fowey Estuary (Hart *et al*., 2014) and Plymouth Sound (Castignetti, 1997) together with material from sample stations used by the Western Channel Observatory (Stations L4, Hillsand, Cawsand; Fig. 5). Other comparative material has come from a shallow marine borehole, located to the east of Jersey, and which recovered a Holocene record in which there was a thin development of 'fossil' maerl estimated to be around 2000–2500 b.p. (Consolaro *et al*., 2014).

Specimens from off-shore St Mawes (Fal Estuary), Cawsand Bay and the Western Channel Observatory Stations L4 and Hillsand (Hart *et al*., 2017) are mostly highly ornamented and can, in most cases, be identified as *Ammonia batava, A. falsobeccarii* and *A. tepida*. The latter species was also recorded by Haynes (1973) from borehole cores in the Dovey Estuary and is also a relatively un-ornamented form. It is, however, very close in appearance to *A. aberdoveyensis*. *Ammonia tepida* was first described from the Caribbean Sea off-shore Puerto Rica and it is somewhat surprising that, coming from a carbonate-rich environment, it lacks much in the way of ornament.

Specimens of *Ammonia* spp. are, as indicated above, highly variable in appearance and there is no discernable distribution pattern, though it is clear that specimens from Plymouth Sound, the Fowey Estuary and Restronguet Creek display less well-developed ornamentation; probably due to the carbonate saturation of the host waters. Specimens collected from off-shore St Mawes (Fal Estuary) and at L4 also show a great variation in levels of ornamentation and 'overgrowth' by additional test material (Fig. 4; 17, 18). Both of these sample sites have normal salinity, pH (8.0–8.1) and temperature, and yet display this significant variation in ornmament. Though not measured at the time of sampling, it is unlikely that ΩCarbonate would generate this level of variability. Using data in Hayward *et al.* (2004) and a range of other interpretations of the species we have identified our morphospecies as follows:

- *Ammonia batava* – deeply incised spiral sutures; imperforate ridges (spiral side) [**Fig. 3**; 1a, b, 2a, b, 3, 4, 5a, b, 6a, b 7: **Fig. 4**; 1, 2];
- *Ammonia falsobeccarii* – triangular spiral side openings, open umbilicus [**Fig. 3**, 8, 9a, b, 10a, b: **Fig. 4**; 3–9]; and
- *Ammonia tepida* – 6 chambers in the final whorl, somewhat inflated, with processes directed into umbilicus [**Fig. 3**; 11, 12a, b, 13a, b: **Fig. 4**; 10–14].

The degree of variability shown by specimens in this off-shore and marginal marine area of South-West England is significant and little understood. With regular sampling of the stations used by the Western Channel Observatory and the various estuaries there is an opportunity to investigate the distribution of the various morphotypes coupled, perhaps, with further rDNA analysis.

Discussion and Summary

The distribution of foraminifera in the upper reaches of the Fal Estuary reflect water depth, salinity, temperature and other environmental parameters, including carbonate saturation (ΩCarbonate). The more open marine aspect of the much larger Fal Estuary is seen in the composition of assemblages around St Mawes and elsewhere (including St Just-in-Roseland). While the beds of living maerl near St Mawes have not been sampled, transported maerl is present in many samples. In the maerl samples from the approach to Falmouth Docks (Sheehan *et al*., 2015) the assemblage of foraminifera is very different to those from the Isle of Bute described by Austin and Cage (2010). In the Falmouth samples the dominance of *Elphidium crispum* suggests post-mortem transport from either fleshy seaweeds or the fronds of sea grasses as none of these individuals were living in the maerl (un-stained by rose Bengal). The presence of open marine taxa (e.g., *Sejunctella earlandi*), some estuarine taxa (e.g., *Haynesina germanica* and *Elphidium williamsoni*) and even salt marsh indicators (e.g., *Jadammina macrescens*) indicates that the species recorded from the maerl represents an admixture of environments. These transported foraminifera have almost certainly been trapped within the branching structure of the maerl and does not indicate a living assemblage with high diversity.

Transport of foraminifera within marginal marine and estuarine environments is not completely understood and, when dealing with both living and dead assemblages, is a constant variable. Murray (1965b, 1987), Murray and Hawkins (1976), Murray *et al.* (1982, 1983) and Hart *et al.* (2017) have reported on such processes, although some recent work on a related topic (e.g., Weinmann and Goldstein, 2017) appears to have missed some of this literature. In their recent paper, Weinmann and Goldstein (2017) report on laboratory cultures that demonstrated the presence of transported propagules (Alve and Goldstein, 2002, 2003, 2010, 2014) or early-stage juveniles (<53 μm) within their re-distributed sediments. Murray (1965b) and Hart *et al.* (2017), in their analysis of benthic foraminifera collected in surface-water plankton tows were reporting on small (<100 μm to ~200 μm) benthic taxa being moved by storm events in the English Channel and off-shore Plymouth.

It is also noted that further work on the *Ammonia* assemblages is required, especially in areas where the Western Channel Observatory have long-running databases on the physico-chemical properties of the water masses and sea floor conditions that may aid our environmental assessments. How many of the species of *Ammonia*, confirmed by rDNA analysis, are identified across a range of marine/estuarine environments is – currently – not known, though it is clear that in estuarine environments (with low ΩCarbonate) most individuals have much less ornamentation.

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APPENDIX: TAXONOMIC NOTES ON FORAMINIFERA

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

Ammobaculites balkwilli Haynes, 1973

Ammonia sp. cf. *A. aberdoveyensis* Haynes = *Ammonia aberdoveyensis* Haynes, 1973.

Ammonia batava (Hofker) = *Streblus batavus* Hofker, 1951.

Ammonia beccarii (Linnaeus) = *Nautilus beccarii* Linnaeus, 1758.

Ammonia falsobeccarii (Rouvillois) = *Pseudoeponides falsobeccarii* Rouvillois, 1974.

Ammonia tepida (Cushman) = *Rotalia beccarii* (Linné) var. *tepida* Cushman, 1926.

Ammoscalaria runiana (Heron-Allen and Earland) = *Haplophragmium runianum* Heron-Allen and Earland, 1916.

Astacolus crepidulus (Fichtel and Moll) = *Nautilus crepidula* Fichtel and Moll, 1798.

Astigerinata mamilla (Williamson) = *Rotalina mamilla* Williamson, 1858.

Bolivina variabilis (Williamson) = *Textularia variabilis* Williamson *typica* Williamson, 1858.

Brizalina variabilis (Williamson) = *Textularia variabilis* Williamson, 1858.

Bulimina elongata d'Orbigny, 1846.

Bulimina marginata d'Orbigny, 1826.

Cibicides lobatulus (Walker and Jacob) = *Nautilus lobatulus* Walker and Jacob, 1798.

Cibicides pseudoungerianus (Cushman) = *Truncatulina pseuoungeriana* Cushman, 1922.

Cribrostomoides jeffreysii (Williamson) = *Nonionina jeffreysii* Williamson, 1858.

Discorbis wrightii (Brady) = *Discorbina wrightii* Brady, 1881.

Eggerella scabra (Williamson) = *Bulimina scabra* Williamson, 1858.

Elphidium crispum (Linnaeus) = *Nautilus crispus* Linnaeus, 1758.

Elphidium earlandi Cushman, 1936.

Elphidium gerthi Van Voorthuysen, 1957.

Elphidium williamsoni Haynes, 1973.

Eponides repandus (Fichtel and Moll) = *Nautilus repandus* Fichtel and Moll, 1798.

Fissurina lucida (Williamson) = *Entosolenia marginata* (Montagu) var. *lucida* Williamson, 1848.

Fissurina quadrata (Williamson) = *Entosolenia quadrata* Williamson, 1858.

Fissurina orbignyana Seguenza, 1862.

Gaudryina rudis Wright, 1900.

Glabratella milletti (Wright) = *Discorbina milletti* Wright, 1911.

Globulina gibba (d'Orbigny) = *Polymorphina* (Globuline) *gibba* d'Orbigny, 1826.

Haynesina germanica (Ehrenberg) = *Nonionina germanica* Ehrenberg, 1840.

Haynesina orbicularis (Brady) = *Nonionina orbicularis* Brady, 1881.

Jadammina macrescens (Brady) = *Trochammina inflata* (Montagu) var. *macrescens* Brady, 1870.

Lagena perlucida (Montagu) = *Vermiculum perlucidum* Montagu, 1803.

Lamarckina haliotidea (Heron-Allen and Earland) = *Pulvinulina haliotidea* Heron-Allen and Earland, 1911.

Lenticulina orbicularis (d'Orbigny) = *Robulina orbicularis* d'Orbigny, 1826.

Massilina secans (d'Orbigny) = *Quinqueloculina secans* d'Orbigny, 1826.

Miliammina fusca (Brady) = *Quninqueloculina fusca* Brady,1870.

Miliolinella circularis (Bornemann) = *Triloculina circularis* Bornemann, 1855.

Miliolinella subrotunda (Montagu) = *Vermiculum subrotundum* Montagu, 1803.

Oolina globosa Montagu, 1803.

Oolina hexagona (Williamson) = *Entosolenia squamosa* (Montagu) var. *hexagona* Williamson, 1858.

Oolina squamosa (Montagu, 1803) = *Vermiculum squamosum* Montagu, 1803.

Parafissurina malcolmsoni (Wright) = *Lagena laevigata* (Reuss) var. *malcolmsoni* Wright, 1911.

Patellina corrugata Williamson, 1858.

Quninqueloculina bicornis (Walker and Jacob) = *Serpula bicornis* Walker and Jacob, 1798.

Quinqueloculina cliarensis (Heron-Allen and Earland) = *Miliolina cliarensis* Heron-Allen and Earland, 1930.

Reophax moniliformis Siddall = *Reophax moniliforme* Siddall, 1886.

Rosalina bradyii Cushman, 1915.

Rosalina globularis d'Orbigny, 1826.

Rosalina williamsoni (Chapman and Parr) = *Discorbis williamsoni*, new name, Chapman and Parr, 1932.

Rotorbinella rosea (d'Orbigny *in* Guérin-Méneville) = *Trochulina rosea* d'Orbigny *in* Guérin-Méneville, 1832.

Sejunctella earlandi Loeblich and Tappan, 1957

Spiroloculina excavata d'Orbigny, 1846.

Spiroloculina rotunda d'Orbigny, 1826.

Spiroplectinella wrightii (Silvestri) = *Spiroplecta wrightii* Silvestri, 1903.

Spirillina vivipara Ehrenberg, 1843.

Spirillina wrightii Heron-Allen and Earland, 1930.

Textularia sagittula Defrance, 1824.

Trifarina angulosa (Williamson) = *Uvigerina angulosa* Williamson, 1858.

Triloculina trihedra Loeblich and Tappan, 1953.

Tritaxis fusca (Williamson) = *Rotalina fusca* Williamson, 1858.

Trochammina inflata (Montagu) = *Nautilus inflatus* Montagu, 1808.

Trochammina ochracea (Williamson, 1858) = *Rotalina ochracea* Williamson, 1858.

Vaginulina subelegans Parr, 1950.