Foraminifera of the Fal Estuary (Cornwall), including taxa associated with Maerl Beds

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The Fal Estuary (Cornwall) 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 their associated microfaunas. This investigation has studied the foraminifera that are found within samples of maerl and the adjacent sediments. Our samples were preserved and then stained with rose Bengal, in order to ascertain the 'living' (stained) assemblage of foraminifera. Only <1% of the taxa associated with the maerl appeared to be living at the time of collection in October 2012, and the assemblage of foraminifera was a mixture of taxa that are characteristic of open marine environments and those characteristic of estuarine and sea grass communities. The presence of pelagic ostracods and centric diatoms supports the notion that at least some of the high foraminiferal diversity reported from the maerl assemblages is the result of transported material trapped within the intricate maerl habitat. Foraminifera from other areas of the Fal Estuary are typical of saltmarsh, estuarine and near-shore marine assemblages reported elsewhere in South-West England.

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Introduction

The designation of Marine Conservation Zones (MCZ) in England is being undertaken by Defra through Natural England (NE) and the Joint Nature Conservation Committee (JNCC). The first two tranches of MCZs were approved in 2013 and 2016, although a further 50+ potential locations have been identified through a nationwide process (Sadri *et al.*, 2011; Lieberknecht *et al.*, 2011; Bureck *et al.*, 2013) to augment an existing network of marine conservation areas around England. Under the Habitats Directive of the European Union (Natura 2000), a number of areas have been listed as Special Areas of Conservation (SAC). One such area is the 6,387.8 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 (Figure 2). This SAC is one of the most important ria 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., Pencuil, Fal, Truro, Carnon, 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 (Figures 1, 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). The Fal Estuary contains both living and dead maerl deposits,

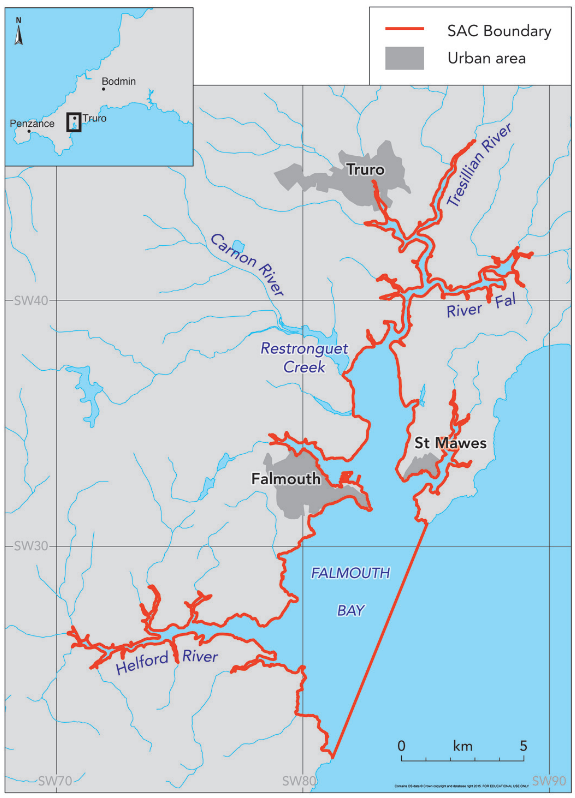

Figure 1. *The boundaries of the Fal and Helford Special Area of Conservation.*

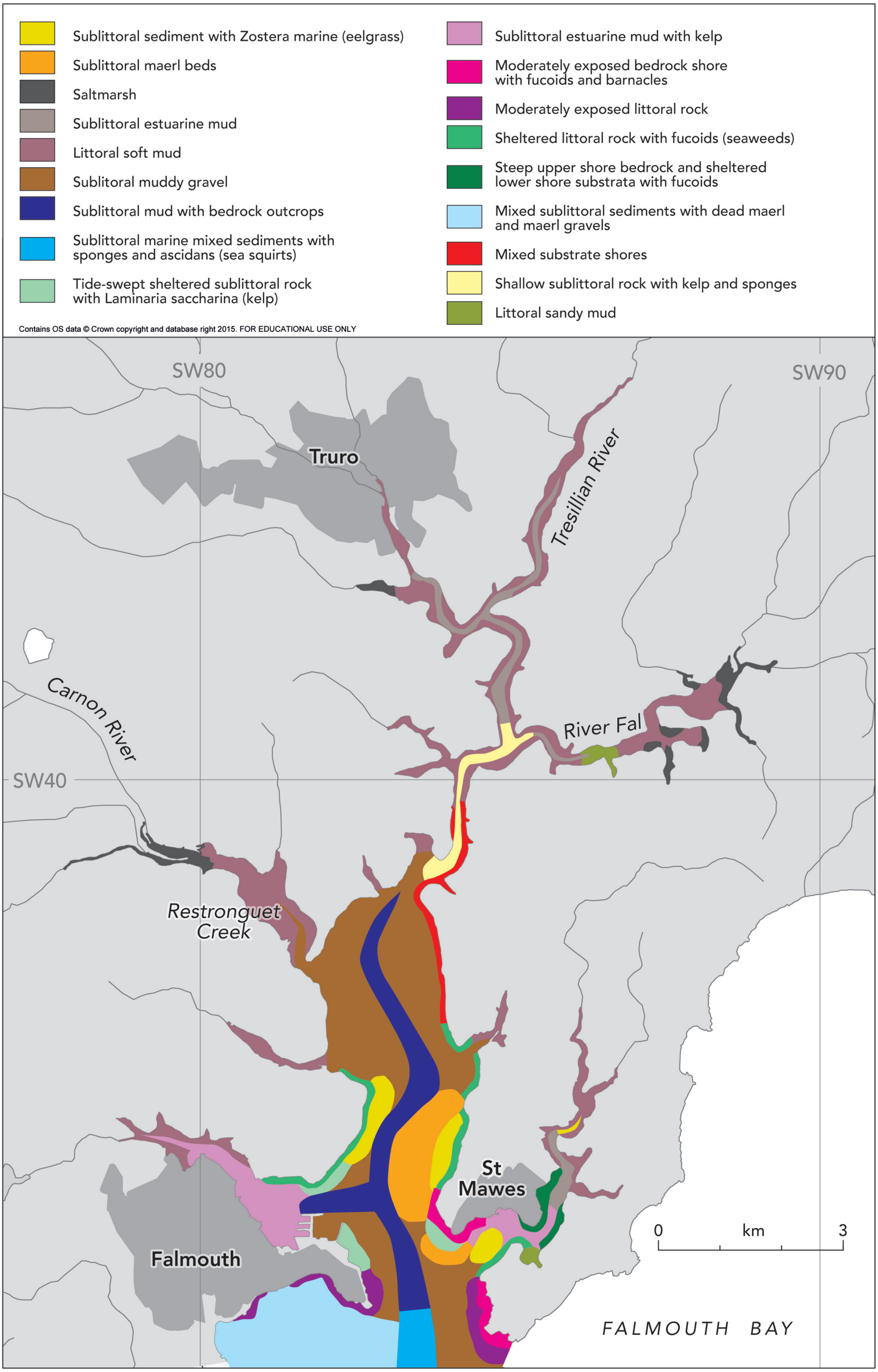

Figure 2. *Distribution of sediments and facies in the Fal Estuary, Carrick Roads, St Mawes Bank and tidal estuaries.*

with a salinity of >30‰ or just below (Bryan and Hummerston, 1973). 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 Environmental, Fisheries and Rural Affairs (Defra): see Hall-Spencer (2005).

Maerl

Maerl is the collective name for a number of species of red seaweeds (Rhodophyta) that develop hard, calcareous skeletons (Corallinaceae). Maerl has twig-like, branching forms and, as the living alga, requires sunlight to grow. They are found down to depths of 51 m in the NE Atlantic Ocean but are usually restricted to depths of <20 m (Peña *et al.*, 2014). Some Corallinaceae encrust rocks and shells but attached forms can often form rhodolith or maerl habitats in near-shore environments (Martin and Hall-Spencer, 2016). In tropical regions (e.g. Brazil) rhodoliths (Figure 3a) can be 10 cm in diameter and have a characteristic internal structure (Pascelli *et al.*, 2013). Rhodoliths are also well-known in the geological record, including the Tata Limestone Formation (mid-Cretaceous) of Hungary (Figure 3b). The maerl requires sufficient water movement (tidal flow or wave action) to remove fine sediment that may restrict growth. Dead maerl accumulates on the sea floor, often with a thin layer of purple/pink-coloured living maerl on the top (Figure 3c). In English waters there are approximately 15 km^2 of maerl habitat, which represents just 0.03% of the near-shore marine environment. The maerl beds of the Fal are, therefore, a significant proportion of the total. 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 South-West England, Brittany, Western Ireland, the Inner Hebrides and Iceland.

Maerl beds are particularly important near-shore habitats as they support a high diversity of benthic, marine, invertebrates (Bosence, 1979). Areas of maerl are a 'Priority Habitat' within the UK Biodiversity Action Plan (see *http://jncc.defra.gov.uk/page-6023* and links to UK BAP priority species and habitats). As a result of devolution, the country-level biodiversity strategies in the UK Post-2010 Biodiversity Framework include 'Habitats of Principal Importance in England' (Natural Environment and Rural Communities (NERC) Act, 2006) which includes maerl beds as being of national importance. Dead maerl accumulates very slowly over thousands of years and can also contain small patches of living maerl such as near the channel into Falmouth Docks. Austin and Cage (2010) showed, in an investigation of two samples, that a maerl bed offshore the Isle of Bute (Scotland) contained a high diversity of foraminifera. A high diversity of foraminifera in maerl beds has also been reported in Recent deposits by Boillot (1964), Blanc-Vernet (1969), Rosset-Moulinier (1972) and Freiwald and Henrich (1994) as well as in Holocene sediments in the south of France (Morhange *et al.*, 2003).

Here, maerl-rich samples from the Fal Estuary have been investigated for their associated foraminifera and, unlike samples studied by Austin and Cage (2010), those investigated in this pilot study were preserved in buffered formalin before being stained with the protoplasmic stain, rose Bengal, in an attempt to distinguish the 'living' (stained) assemblage and the 'dead' (un-stained) component of the assemblage, some of which may have been transported onto the maerl after death.

Material and methods

Aside from the samples of maerl from the Fal Estuary (see Sheehan *et al.*, 2015), a number of other samples were collected from the headwaters of the Tresillian River near Pencalenick [SW 860 454], Fal River near Lamorran [SW 877 417], Percuil River near Trethem Mill [SW 862 363], Calenick Creek east of Calenick [SW 827 432], Tallack's Creek east of Devoran [SW 802 389], and in a boatyard near St Just-in-Roseland [SW 847 357]. The methods employed were comparable to those used by Stubbles (1993, 1999), Olugbode *et al.* (2005) and Hart *et al.* (2014). All 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 (Figure 4a). All samples were

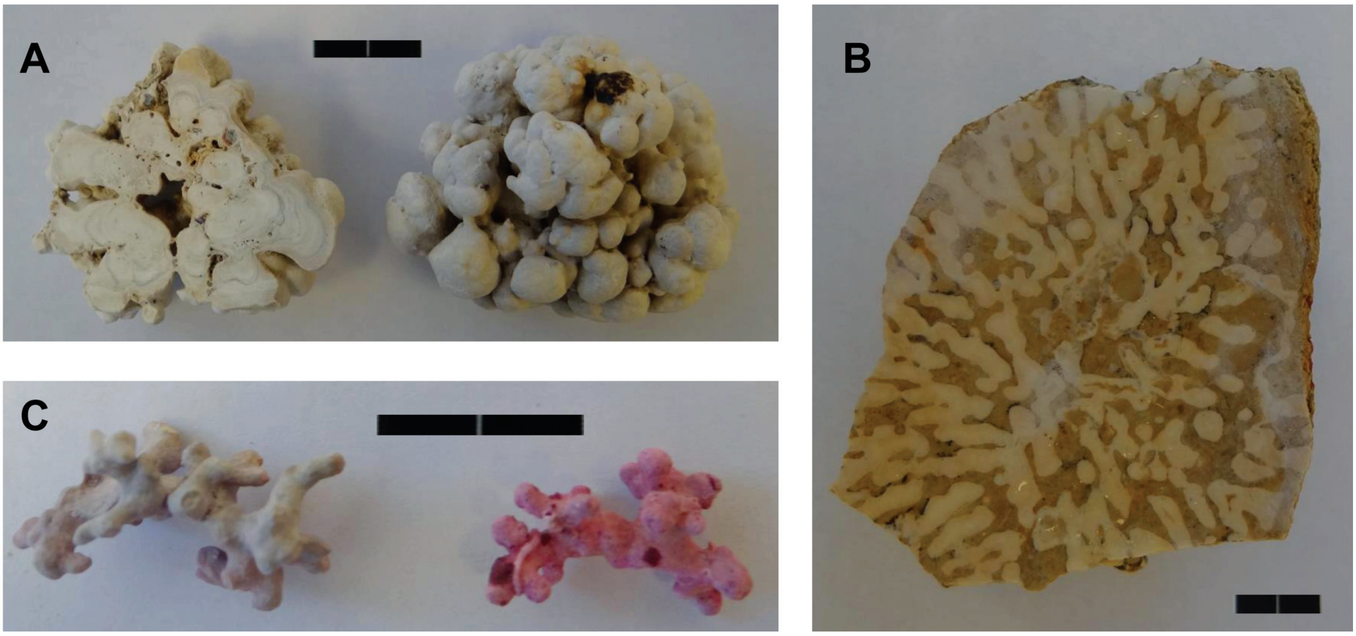

Figure 3. *Examples of rhodoliths, including maerl, from the Fal Estuary. (**a**) A large modern rhodolith from the coastline of Sergipe (Brazil), scale bar = 1 cm. (**b**) Fossil rhodolith from the mid-Cretaceous of Hungary, scale bar = 1 cm. (**c**) Maerl from the Fal Estuary with the specimen on the left (un-stained) which was dead at the time of collection while the specimen on the right (stained) may have been living at the time of collection, scale bar = 1 cm.*

*Figure 4. Collection of field samples at Trethem Mill at the tidal limit of the Percuil River. (**a**) Sample collection within the 10 cm diameter plastic ring. (**b**) Looking along the Percuil River, downstream towards St Mawes.*

subsequently washed on a 63 µm large diameter sieve to remove most of the fine sediment. The residue was then placed in rose Bengal organic stain (1 g per litre de-ionized water) for three hours before being re-washed on a 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 7100FE Field Emission scanning electron microscope.

The two bulk maerl samples collected from the Fal Estuary in October 2012 were preserved in buffered formalin and then washed on a 2 mm sieve (to remove the maerl and other shell fragments). The finer material was then washed on a large diameter 63 µm sieve, after which they were soaked in the protoplasmic stain, rose Bengal, for three hours before being washed again on the 63 µm sieve, filtered and then dried at <40°C in a cool oven. Some of this maerl was stained bright pink and presumed to have been 'living' at the time of collection. The other components of the assemblage were studied in the range of size fractions described above.

The maerl 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 adherent forms.

FORAMINIFERA

Foraminifera were recorded in every sample, often in large numbers. Almost all the taxa are well known in the estuarine and coastal waters of Cornwall and South Devon (Millett, 1885; Heron-Allen and Earland, 1930; Murray, 1965, 1970, 1971; Castignetti, 1997; Stubbles, 1993, 1999; Olugbode *et al*., 2005; Hart *et al*., 2014). The distribution of foraminifera 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, a much larger system with many more rivers entering from a much larger catchment, which was extensively mined in the 19th 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 is the primary reason for the exclusion of Restronguet Creek from the SAC, 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. Samples collected in 2004/2005 from Restronguet Creek still recorded significantly elevated numbers of deformed foraminifera, as reported by Olugbode *et al*. (2005). In this investigation deformed foraminifera have been recorded although the numbers, away from Restronguet Creek, are comparable to those reported in the Fowey Estuary (Hart *et al*., 2014). Examples of deformed taxa are shown in Figure 5 (12, 15), and these species have been selected for illustration as they are typical of those recorded in the 2015 sampling campaign.

Some of the foraminifera collected from the Fal Estuary are illustrated in Figure 5, although many of the taxa have already been illustrated in Hart *et al*. (2014, figs 4, 5). The species encountered are listed in the Appendix and their numbers presented in Table 1 which gives the total counts of each species, together with the percentage of the total assemblage. In this pilot study the live/dead separation is not presented as this work is still on-going. 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. These assemblages can also be identified for the sample locations around the Fal Estuary. As all the collected samples 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 providing the closest assemblage to the saltmarsh seen at Shirehall Moor near Lostwithiel (Assemblage 1). *Miliammina fusca* is the dominant species found in Calenick Creek and at Trethem Mill, although *Haynesina germainica* and *Elphidium williamsoni* are the dominant species in the Tresillian River, Fal River (Lamorran) and Tallacks' Creek (Restronguet Creek). 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 sample confirmed that this is still the case. *E. williamsoni* and *H. germanic*a 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.

The assemblage from the maerl samples was, as expected, quite different in being dominated by *Elphidium crispum, Astigerinata mamilla, Quinqueloculina* spp. and *Rosalina globularis*. Despite the sample being stained with rose Bengal following normal procedures, few individuals took up the stain, even though some of the maerl appears to have been living when collected (bright pink in colour). This may be due to the time of sampling as, by October in most of the estuaries in South-West England (e.g. Plymouth Sound; see Castignetti, 1997), the

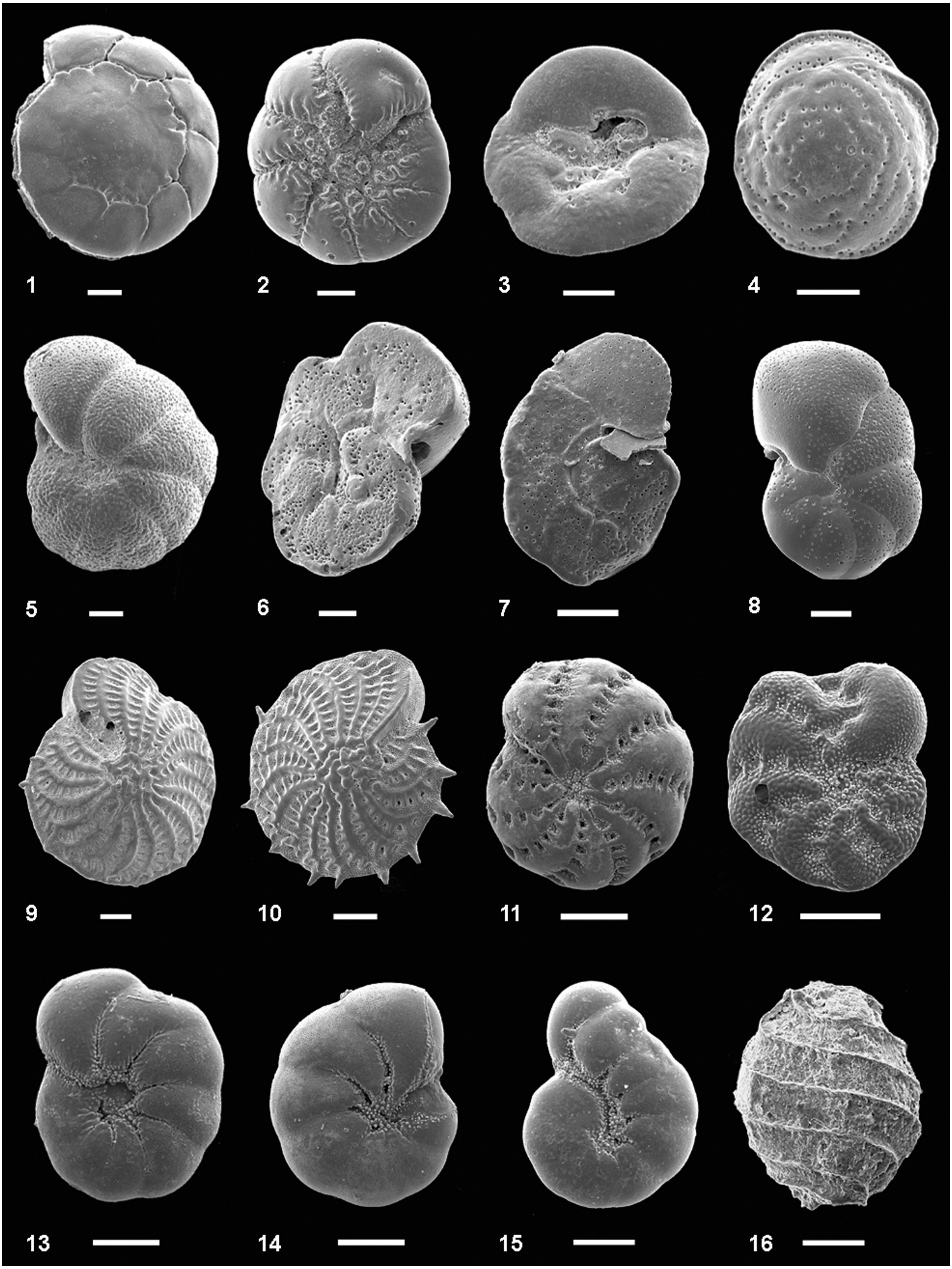

Figure 5. *Foraminifera and a charophyte from the Fal Estuary.* ***(1, 2)*** Ammonia batava *(Hofker, 1951).* ***(3, 4)*** Astigerinata mamilla *(Williamson, 1858).* ***(5-8)*** Cibicides lobatulus *(Walker & Jacob, 1798).* ***(9, 10)*** Elphidium crispum *(Linné, 1758).* ***(11)*** Elphidium williamsoni *Haynes, 1973.* ***(12)*** Elphidium earlandi *Cushman, 1936.* ***(13, 14, 15)*** Haynesina germanica *(Ehrenberg, 1840), with* ***(15)*** *showing deformed growth pattern in final whorl.* ***(16)*** Nitella opaca *(C. Agardh ex. Bruzelius) C. Agardh (1824) from the Percuil River at Trethem Mill. This charophyte oospore is badly preserved, indicating that it has been transported prior to sedimentation in the upper estuarine muds of the sample location (see Figure 4a). Scale bars all 100 µm.*

	Calenick Creek	Tresillian River (U)	Tresillian River (L)	Trethem Mill	Fal River Lamorran	Tallack's Creek	St Just Boatyard	Maerl
J.macrescens	32(11%)	1(0.5%)	7(2.0%)	9(2.5%)	2(0.5%)	-	-	1(0.25%)
T.inflata	-	-	-	1(0.3%)	-	-	1(0.5%)	-
M.fusca.	247(84%)	7(2.5%)	3(1.0%)	168(49%)	34(9.5%)	-	2(1%)	-
H.germanica	11(4%)	267(92%)	279(86%)	102(29.8%)	194(53%)	191(73.75%)	106(46%)	7(1.5%)
E.williamsoni	3(1%)	14(5%)	14(4.0%)	40(11.8%)	72(20%)	63(24.25%)	73(31.5%)	13(3%)
***Quinque.* spp.**	-	-	14(4.0%)	15(4.3%)	25(7%)	-	20(8.5%)	84(20%)
A.mamilla	-	-	1(0.5%)	-	-	-	-	109(26%)
C.lobulatus	-	-	2(1.0%)	1(0.3%)	-	-	1(0.5%)	22(5%)
E.crispum	-	-	1(0.5%)	-	-	-	-	128(30.5%)
R.globularis	-	-	1(0.5%)	-	-	-	-	18(4.25%)
O.squamosa	-	-	1(0.5%)	-	-	-	-	-
A.aberdovey.	-	-	-	7(2.0%)	31(8.5%)	5(2%)	12(5%)	-
R.moniliformis	-	-	-	-	5(1.5%)	-	16(7%)	-
A.batava	-	-	-	-	-	-	-	6(1.5%)
Other marine	-	-	-	-	-	-	-	8%
Assemblage	2	2/3	2/3	2/3	2/3	2/3	4	(mixed)

Table 1. *Foraminifera assemblage counts of samples from the Fal Estuary and adjacent creeks. Assemblage numbers in the lowest row relate to those used by Hart* et al. *(2014). Abbreviations: the two samples from the Tresillian River came from upper (U) mud-flats and lower (L) mud-flats,* Quinque. *spp.* = Quinqueloculina *spp. and* A. aberdovey. = A. aberdoveyensis. *The assemblage numbers given in the bottom row refer to those established for the Fowey Estuary (Hart* et al.*, 2014).*

living assemblage of foraminifera is normally quite reduced.

The species present in the maerl samples included a mixture of saltmarsh (*Jadammina macrescens*), estuarine (*H. germanica, E. williamsoni*) and open marine species (*Ammonia batava, Trochammina ochracea, Cribrostomoides jeffreysii, Astigerinata mamilla, Fissurina* sp., *Parafissurina* spp., *Oolina* spp. *Quinqueloculina cliarensis, Q. bicornis, Brizalina* sp., *Globocassidulina* sp., and *Sejunctella earlandi*). There were also rare centric diatoms indicating an open marine source as well as a few elliptical forms more typical of estuarine assemblages. Some species of foraminifera had specimens of the coccolith *Emiliania huxleyi* sticking to their chambers: again indicating an open marine source although coccolithophores are known from some estuaries in South-West England (e.g. Plymouth Sound). The most common foraminiferan in the counted material was *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 different to the samples collected in the Fal Estuary. Stravanan Bay is not estuarine and although there are sea grass meadows in the Firth of Clyde, none are thought to be close to Stravanan Bay. 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. These data from Tor Bay suggest that, by October, when the maerl 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 trapped with a mixture of other marine and estuarine taxa. Any maerl sample provides only a snapshot of the accumulated sediment but it is clear that the recorded assemblage appears to be an admixture of transported marine, estuarine and sea grass communities. Sampling in May-July would provide a more definitive view of a maerl-associated living assemblage which may include adherent forms, such as Patellina corrugata, as recorded on maerl in the Firth of Clyde (Hall-Spencer, 1994).

Charophytes

In a sample from the Percuil River near Trethem Mill (Figure 4a) a number of charophyte oospores have been recorded (Figure 5 (16)). Charophytes are freshwater 'green algae', colloquially known as stoneworts. This name is derived from the observation that the stems of these algae, and the oospores, are often encrusted with calcium carbonate. This calcification has given the stoneworts a long geological record extending back to the Devonian Rhynie Chert environment. The Characea and Nitellacea have a 200 million year fossil record, with modern *Chara* represented by 16 species and *Nitella* represented by eight species. Stoneworts require a clear, low-nutrient, still, freshwater environment and their presence can be an excellent indicator of water quality (Stewart, 2004).

It is, therefore, significant that the sample collected from the Percuil River contained oospores identified as *Nitella opaca* (C. Agardh ex. Bruzelius) C. Agardh (1824). This is the type species of the genus *Nitella*, and the species identification has been confirmed by N.F. Stewart (pers. comm., 2015). Further details on this species are available in Bryant and Stewart (2011) and Guiry (2015). This is the first record of this species in the Roseland area (Stewart and Church, 1992), although its occurrence in the estuarine muds of the Percuil River raises the question of where these algae are living. The normal habitat would be lakes or brooks with clean, fresh water (Stewart, 1996), though there are records from slightly brackish waters.

Specimens of *Nitella opaca* are normally 5-50 cm high with an axis (stem) ~1 mm in diameter. The fresh oospores are usually dark (chestnut to black) in colour and the normal occurrence is in lakes and brooks. Stewart (2004) records six important locations in South-West England: Braunton Burrows, Newton Abbot clay-pits and heaths, Slapton Ley National Nature Reserve, Tinhay Quarry (South Hams), Widdicombe Ley (South Hams) in Devon and heaths and quarries on the Lizard Peninsula in Cornwall. The alga was not observed in the sampling area and so is presumed to be living upstream in the Percuil River. It would be interesting to determine the location, in case any conservation measures are required to protect the habitat.

Summary

The distribution of foraminifera in the upper reaches of the Fal Estuary follow predicted patterns of distribution and reflect the local water depth, salinity and temperature. The communities from St Just-in-Roseland appear more 'marine' than those reported in the Fowey Estuary, probably reflecting the much wider opening of the estuary to the open sea and the resulting higher salinities. Our maerl samples contained assemblages of foraminifera that were different in character from that recorded by Austin and Cage (2010) in a comparable environment off the Isle of Bute in Scotland. The dominance of *Elphidium crispum* appears to reflect a derivation from fleshy seaweeds or the fronds of sea grasses, as none of these individuals were alive at the time of sampling. The presence of rare marine species (e.g. *Sejunctella earlandi*) and some estuarine taxa (e.g. *Haynesina germanica* and *Elphidium williamsoni*) indicates that the species recorded from the maerl represents an admixture of environments and that it includes transported foraminifera, trapped within the irregular surface of the algae. The presence of *Nitella opaca i*n the Percuil River is interesting as this is the first record of this species in the Roseland area of Cornwall.

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

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

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

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

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

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

Elphidium williamsoni Haynes, 1973.

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

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

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

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

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 Siddal, 1886.

Rosalina globularis d'Orbigny, 1826.

Sejunctella earlandi Loeblich and Tappan, 1957

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

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