THE WESTERN CHANNEL OBSERVATORY: BENTHIC FORAMINIFERA IN THE PLANKTON FOLLOWING STORMS

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The Western Channel Observatory was established by the Natural Environment Research Council (NERC), with Plymouth Marine Laboratory managing two autonomous buoys that are located to the south of Plymouth in the English Channel (Stations L4 and E1). These two locations are now monitored continually and there is regular sampling of the water column and the sea floor at both locations. At Station L4, despite being in waters with a depth of 50 m, benthic foraminifera are regularly found in the surface water plankton samples. Some of these benthic foraminifera appear to contain algal symbionts, indicating that they may have been living at the time of collection. The redistribution of benthic foraminifera within sediment samples by means of storm events has significant implications for the palaeoecological interpretation of 'fossil' sediments. Recolonization by foraminifera, following disturbance, could well be facilitated by this mechanism which has only rarely been reported in the literature. It is clearly limited to depths impacted by fair weather (~ 20 m) or storm wave base (>50 m). Data gathered thus far certainly indicate that the greater the severity of the storm, the larger the number of benthic foraminifera in the plankton tows and the greater their overall size.

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INTRODUCTION

In 2007, Plymouth Marine Laboratory (PML) was awarded the funds to construct two autonomous buoys as part of the 'Oceans 2025' programme of NERC. The buoys have been located at stations L4 and E1 (see Fig. 1), where they are recording a comprehensive data set, including sea surface temperature, salinity, oxygen, turbidity, etc. The data are transmitted to an on-shore station at Rame Head.

The Western Channel Observatory (WCO) – which was officially established in 2005 – uses a number of long-standing reference points, with Station E1 recording hydrographic data from 1903 and L4 for a comparable period of time. Both stations are now recording hourly data readings, to which can be added regular water sampling, plankton tows, CTD records and sediment samples. The science of the WCO has recently been described by Smyth *et al.* (2015).

Station L4 (50° 15´N, 4° 13.2´W; 50 m water depth) is located 13 km off Plymouth, while Station E1 (50° 02´N, 4° 23´W; 75 m water depth) is situated 40 km off-shore, south of the Eddystone Rock. The inner site, L4, is tidally influenced and also receives freshwater from the River Tamar and the River Plym (O'Brian *et al.*, 2013). L4 has been sampled on a weekly basis by PML since 1988, extending the earlier time-series maintained by the Marine Biological Association of the UK (Harris, 2010). Station E1, established in 1903 by the MBA, was re-started by PML/MBA in 2002 and is now the longest hydrographic series in the world (Karl, 2010). It is part of a transect that extends from off-shore Plymouth (Station E1) to west of Ushant (Station E5): see Smyth *et al.* (2015).

FORAMINIFERA

Sampling at Station L4 regularly includes the taking of sediment box-cores (Fig. 2) and sub-samples taken from the boxes have, occasionally, been studied for foraminifera; the last being in June 2016. These samples contain a diverse and abundant assemblage of benthic foraminifera consistent with the species recorded by Heron-Allen and Earland (1930), Murray (1965a, 1970, 1971,1986), Castignetti (1997) and Manley (1997). Work on these assemblages is on-going and the changes down-core are being documented. There is, presently, no indication of how far back in time our sub-surface record extends.

In spring 2016, following severe storms, it was noted that significant numbers of benthic foraminifera were being found in surface water plankton tows and those collected at 10 m below the surface. That benthic foraminifera can be transported is not new as, once dead, the test is effectively a grain of sediment. This has previously been described by Jones (1958). In January 1962, however, plankton samples collected by R.V. *Sarsia* (by the Marine Biological Association of the U.K.) in the English Channel are recorded as containing significant numbers of dead benthic foraminifera (Murray, 1965b). These samples from offshore Lizard Head, Ushant and a location in the mid-Channel of the English Channel were from relatively deep-water sites (78 m, 107 m and 93 m respectively) and the plankton samples were from both near-surface and 10 m water depth: see Murray (1965b, table 1). Murray (1965b, p. 157) also noted that such re-working may well occur both during, and after, severe storms, with all the sites being within the range of storm wave-base.

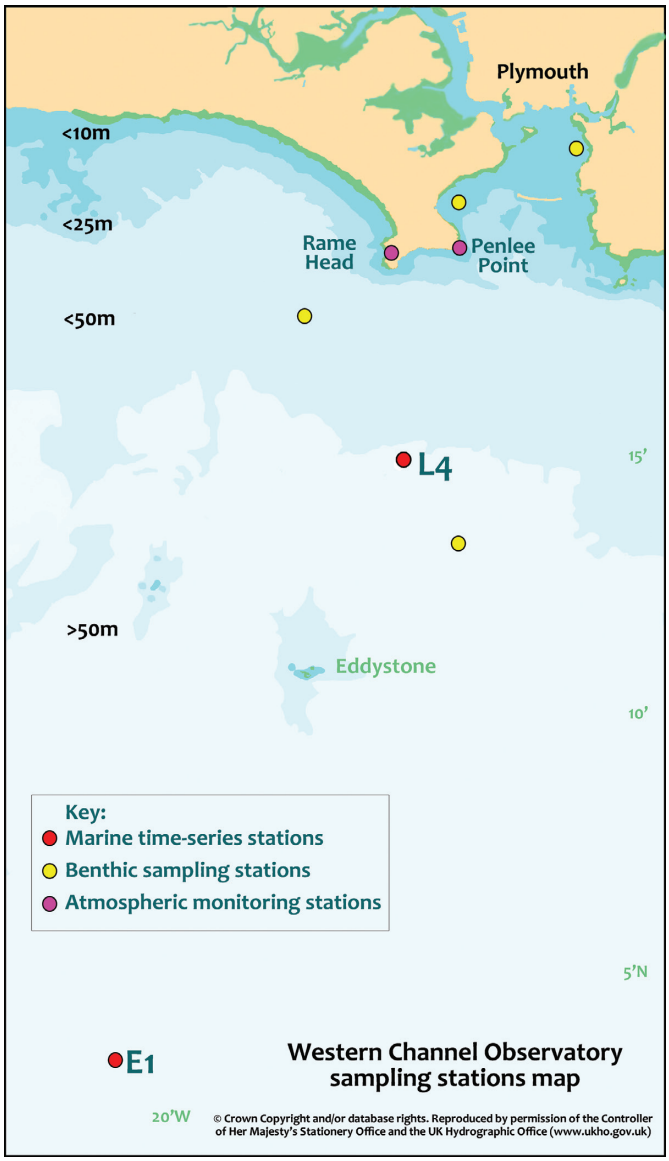

Figure 1. *Map of the sea area adjacent to Plymouth showing the location of sampling sites and the location of Stations L4 and E1.*

The specimens recorded by Murray (1965b, table 1) are small (15-20 µm) and, being collected in January, almost certainly dead. The question is, therefore, whether storms during the summer months (or even the winter months) transport living foraminifera significant distances by lifting them into the water column? In sediments impacted by storm wave-base, this mechanism may provide a method of re-colonization following disturbance such as:

- Anoxia (e.g., Jorissen, 1999 and Alve, 1995a)
- Turbidity currents (e.g., Kaminski *et al.*, 1996);
- Volcanic eruptions and ash-fall events (e.g., Hess *et al.*, 2001); and
- Pollution and/or human impact (e.g., Alve 1995b).

The alternative method of re-colonization by propagules (Alve and Goldstein, 2002, 2003, 2010) can only occur if the time elapsed since disturbance is within the life span of the propagules. With transportation by storms, the living foraminifera could be transplanted very quickly and, if living on 'touchdown' may develop a new population within a growing season or two.

Samples and Results

In winter 2015 and spring 2016 the waters around the United Kingdom were subjected to a series of significant storms. These attracted media attention as, for the first time, these storms were given names. Several of these impacted on the areas being monitored by stations L4 and E1. The storms were: ***Abigail***: 12th to 13th November, 2015; ***Barney***: 17th to 18th November, 2015; ***Clodagh***: 29th November, 2015; ***Desmond***: 5th to 6th December, 2015; ***Eva***: 24th December, 2015; ***Frank***: 29th to 30th December, 2015; ***Gertrude***: 29th January, 2016; ***Henry***: 1st to 2nd February, 2016; ***Imogen***: 8th February, 2016; ***Jake***: 2nd March, 2016; and ***Katie***: 27th to 28th March, 2016. While many of these storm events were centred on Wales, the north of England and Scotland, ***Imogen*** recorded gusts of 81 mph on the Isle of Wight, 69 mph gusts at Culdrose (Cornwall) and 69 mph gusts at Portland Bill. Winds of ~70 mph were widespread in the English Channel.

For this pilot study, samples collected on the 10th February 2016 at Station L4 were studied as these were the closest in time to storm ***Imogen***. Samples were collected from the surface waters using a 20 µm mesh plankton net, stored in neutral formaldehyde and inspected/imaged using a Leica DMI4000B light microscope. The samples contained abundant diatoms, dinoflagellates, rare silicoflagellates and other phytoplankton, together with a significant number of benthic foraminifera and rare planktic foraminifera. Samples also contained significant quantities of micro-plastic fibres. The tiny planktic foraminifera (*Globigerina* s.l.) have no characteristics visible that allows their specific identification. Collected in February, they may have been living in the water column but – more likely – had been picked up from the sea floor by the strong wave action during storm ***Imogen***.

The benthic foraminifera are generally small (< 150 µm), as reported previously by Murray (1965b). A wide range of taxa are recorded (Fig. 3), including some that are tentatively identified to species level (e.g., *Glabratella millettii*, *Patellina* sp. cf. *P. corrugata*, *Brizalina pseudopunctata*, *Fissurina* sp. cf. *F. lucida*). Many of the planispiral or trochospiral species are difficult to identify at the species level (e.g., *Ammonia, Elphidium, Haynesina*, etc.) as surface ornamentation is either not visible or not fully developed in such juvenile specimens. Some of the lagenids show details of entosolenian tubes of varying lengths, including those where the tube extends completely across the single chamber to those where it occupies only ~30% of the internal diameter. Some tests appear to be empty while others contain sediment particles (of varying grain size), often totally filling the chambers. It is rather surprising that individuals completely infilled with sediment could be transported up into the surface waters.

At Station L4 the species recorded in the plankton appear to be those recorded in the sea floor samples immediately adjacent to the site, but there is the possibility that some of the species may have been picked up from closer to the shore in shallower waters. On-going work on the benthic foraminifera in the area is attempting to determine if specimens from shallower water are being transported into the area of L4 as this would have implications for any palaeoecological interpretations not limited to living taxa. This would also have implications for the interpretation of fossil material where a mixing of foraminifera from different environments could lead to the incorrect determination of water depth or community structure.

Benthic foraminifera in the adjacent marine area

Benthic foraminifera have been studied in the marine area adjacent to Plymouth since the pioneering research offshore South Cornwall by Fortescue William Millett (1885). On his death in Brixham, in 1915, his collections and microscope slides were transferred to the Natural History Museum in London by Edward Heron-Allen (Hodgkinson, 2006; Hart *et al.*, 2011), who

Figure 2. *Box-core sampling in operation at Station L4 from the deck of M.V. Plymouth Quest.*

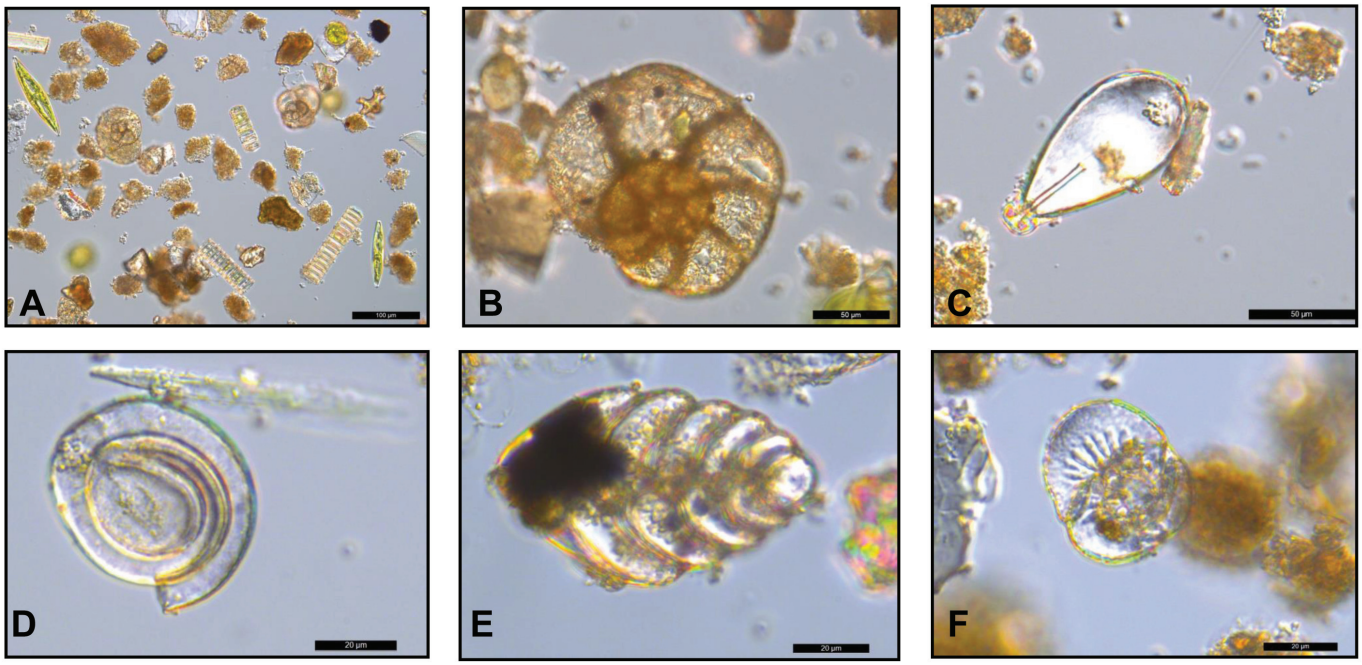

Figure 3. *Foraminifera collected in a surface-water plankton tow on the 10th February, two days after storm Imogen.* ***(A)*** Globigerina *sp. and* Ammonia *sp., together with colonial diatoms;* ***(B)*** Ammonia *sp. with sediment infilling the chambers;* ***(C)*** Fissurina *sp. cf.* F. lucida *with the entosolenian tube clearly visible;* ***(D)*** Cyclogyra *sp. cf.* C. involvens*;* ***(E)*** Brizalina spathulata*;* ***(F)*** Glabratella millettii. *Scale bars are as follows:* ***A*** *– 100 µm;* ***B***, ***C*** *– 50 µm;* ***D***, ***E***, ***F*** *– 20 µm.*

Species	Cawsand	L4	Hillsand	Cawsand (%)	L4 (%)	Hillsand (%)
Ammonia spp.	384	451	379	29.05	58.34	40.71
Quinqueloculina seminulum	158	46	83	11.95	5.95	8.92
Elphidium crispum	288	12	3	21.79	1.55	0.32
Cibicides lobatulus	127	44	70	9.61	5.69	7.52
Massilina secans	94			7.11		
Eggerella scabra	66	4	16	4.99	0.52	1.72
Asterigerinata mamilla	29	41	52	2.19	5.30	5.59
Bulimina elongata	22	26	61	1.66	3.36	6.55
Haynesina depressula	19	18	1	1.44	2.33	
Elphidium articulatum	13	2	2	0.98	0.26	
Quinqueloculina bicornis	11	13	16	0.83	1.68	1.72
Ammoscalaria spp.	10	14	17	0.76	1.81	1.83
Planorbulina mediterranensis	10	4	24	0.76	0.52	2.58
Quinqueloculina cliarensis	9	3	1	0.68	0.39	
Quinqueloculina oblonga	9	1	9	0.68	0.13	
Haynesina germanica	8			0.61		
Elphidium gerthi	7		1	0.53		
Miliolinella subrotunda	6			0.45		
Haynesina orbicularis	5			0.38		
Gaudryina rudis	5	35	54	0.38	4.53	5.80
Reophax spp.	3	7	13	0.23	0.91	1.40
Quinqueloculina dimidiata	3			0.23		
Quinqueloculina lata	3			0.23		
Gavelinopsis praegeri	3	8	6	0.23	1.03	0.64
Rosalina williamsoni	3	2		0.23	0.26	
Lagena lyelii	2	1		0.15	0.13	
Brizalina variabilis	2	2	1	0.15	0.26	
Gabratella millettii	2	4	64	0.15	0.52	6.87
Bulimina marginata	2	4	5	0.15	0.52	
Bulimina elongata *var. lesleyae*	2	1	2	0.15	0.13	0.21
Miliolinella circularis	2			0.15		
Spiroloculina rotunda	2		1	0.15		
Spiroloculina excavata	2		1	0.15		0.11
Trochammina ochracea	2			0.15		
Brizalina spathulata	1	2	4	0.08	0.26	0.43
Trifarina angulosa	1	5	4	0.08	0.65	0.43
Elphidium earlandi	1	1		0.08	0.13	
Rosalina globularis	1	4		0.08	0.52	
Bulimina gibba	1	9	14	0.08	1.16	
Amphicoryna scalaris	1			0.08		
Cyclogyra involvens	1			0.08		
Textularia sagittula	1	2	6	0.08	0.26	0.64
Planorbulina distoma Terquem	1			0.08		
Fursenkoina fusiformis		1	4		0.13	0.43
Globulina sp. cf. *G. gibba* [fistulose form]		1			0.13	
Epistominella sp.		1			0.13	
Parafissurina malcomsoni		1			0.13	
Planulina sp.		1			0.13	
Oolina hexagona		1	4		0.13	0.43
Cancris oblongus		1	1		0.13	0.11
Pyrgo depressa			1			0.11
Cancris auricula			1			0.11
Lagena perlucida			1			0.11
Fissurina orbignyana			3			0.32
Parafissurina sp. cf. *P. malcomsoni*			1			0.11
Laryngosigma lactea			1			0.11
Trochammina sp. indet.			1			0.11
Lamarckina sp. cf. *L. haliotidea*			1			0.11
Fissurina lucida			1			0.11
Cassidulina sp. cf. *C. obtusa*			1			0.11
TOTAL	1322	773	931	100.00	100.00	100.00

Calcareous
Agglutinated
Porcellaneous

Table 1. *The benthic foraminifera recorded at Cawsand Bay, L4 and Hillsand. Where the record is given as a %, this represents the numbers of individuals recorded in a count of the 150–250 µm size fraction.*

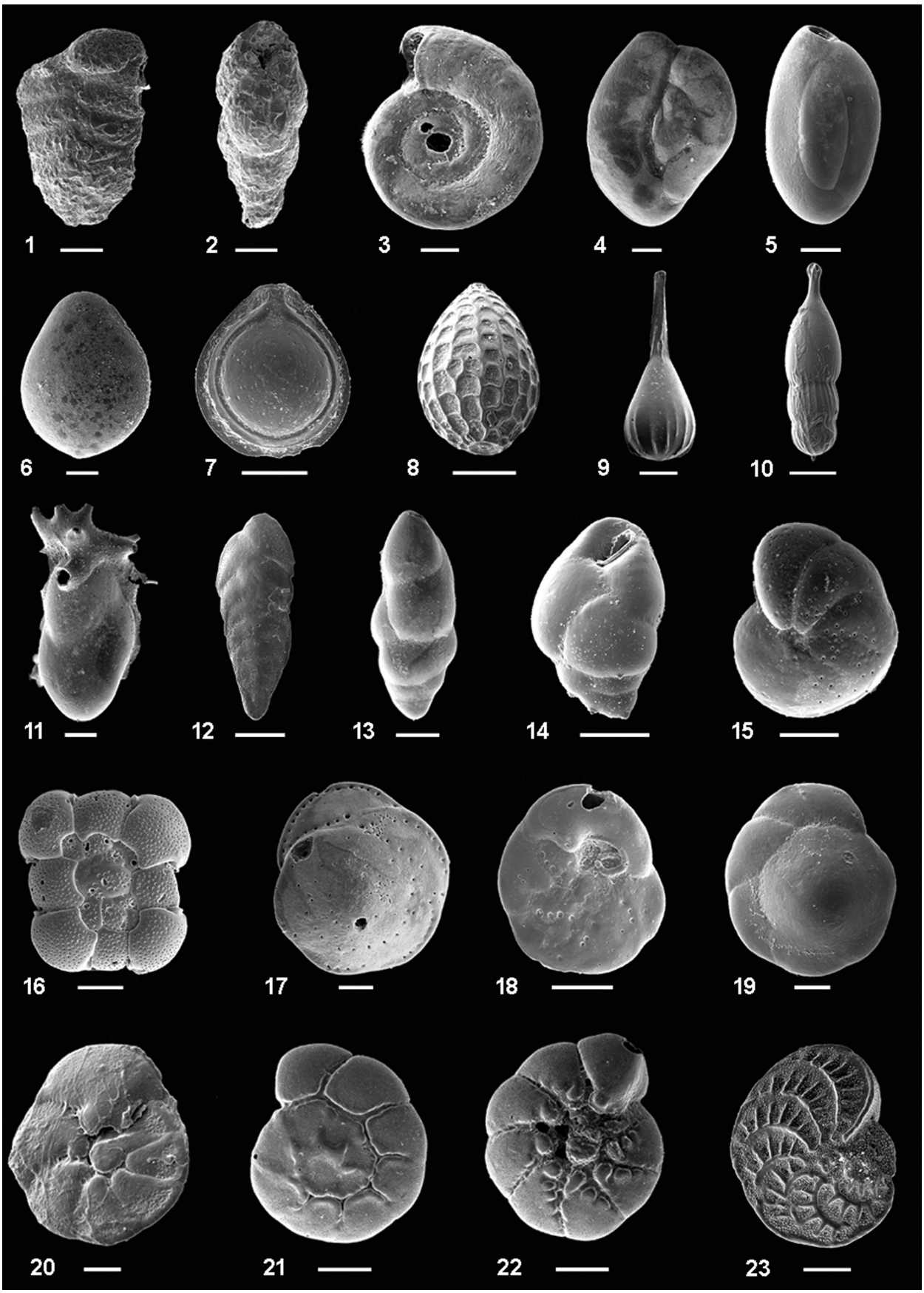

Figure 4. *Scanning electron micrographs of foraminifera species from the L4 (L), Hillsand (H) and Cawsand (C) sampling stations. All scale bars represent 100 µm.* ***(1)***. Textularia sagittula, *(H).* ***(2)***. Eggerella scabra, *(C).* ***(3)***. Cyclogyra involvens, *(C).* ***(4)***. Massilina secans, *(C).* ***(5)***. Quinqueloculina seminulum, *(C).* ***(6)***. Fissurina lucida, *(H).* ***(7)***. Lagena perlucida, *(H).* ***(8)***. Oolina hexagona, *(H).* ***(9)***. Parafissurina malcomsonii, *(H).* ***(10)***. Amphicoryna scalaris, *(C).* ***(11)***. Globulina *sp. cf.* G. gibba *[fistulose form], (L).* ***(12)***. Brizalina spathulata, *(C).* ***(13)***. Bulimina elongata, *(C).* ***(14)***. Bulimina gibba, *(H).* ***(15)***. Cibicides lobatulus, *(H).* ***(16)***. Planorbulina mediterranensis, *(L).* ***(17, 18)***. Asterigerinata mamilla, *(H), dorsal view* ***(17)*** *and ventral view* ***(18)***. ***(19, 20)***. Gavelinopsis praegeri, *(C), dorsal view* ***(19)*** *and ventral view* ***(20)***. ***(21, 22)***. Ammonia *spp., (C), dorsal view* ***(21)*** *and ventral view* ***(22)***. ***(23)***. Elphidium crispum, *(C).*

continued working on the foraminifera of the Plymouth region with Arthur Earland (Heron-Allen and Earland, 1930). Subsequent work by Murray (1965a, 1970, 1971, 1986), Castignetti (1997) and Manley (1997) has continued building our knowledge of the near shore to off-shore assemblages.

The stations monitored for benthic organisms by the WCO (Fig. 1) include Cawsand Bay, L4 and the immediately adjacent Hillsand location (Fig. 1). Samples collected in June 2016 have added to our knowledge of the Plymouth region. The surface sediments in Cawsand Bay contained very few living foraminifera, with only a very few, juvenile forms, taking up the rose Bengal stain. The assemblage was dominated by *Ammonia* spp. (Table 1), and the species richness was relatively low (44). Samples from the surface sediments of stations L4 and Hillsand recorded slightly lower species richness: 36 at Station L4 and 41 at Hillsand. All these figures are typical of sediment samples collected in the Plymouth off-shore area. Some representative taxa are illustrated in Figure 4, all of which were imaged using a JEOL JSM6610LV scanning electron microscope using a bean voltage of 15 Kv and a 9 mm working distance.

Of particular interest is the specimen of *Globulina gibba* d'Orbigny with a fistulose growth covering the normal, terminal aperture. Such specimens are rarely observed and there is some uncertainty as to the function of this structure. The normally smooth species has a number of tubular, inter-linked, projections with the surface covered in small tubercles or spine bases. Comparable specimens have been described by Barnard (1962) from the Upper Cretaceous of southern England and by Cushman and Ozawa (1930, p. 5) from a number of different ages and locations. The only suggestion as to the function of the fistulose growth form is that of Pozaryska and Voigt (1985), who described polymorphinids wedged in the branches of bryozoans apparently using the fistulose tubes as holdfasts. These individuals were described from the Upper Cretaceous of the Maastricht area of The Netherlands; chalk sediments deposited in relatively shallow waters. There have been no further descriptions of this phenomenon, though all the samples close to L4 and Hillsand contained large numbers of fragmented bryozoans.

Summary

Samples collected from Station L4 on 10th February 2016 have been shown to contain relatively large numbers of benthic (and some planktic) foraminifera. This confirms the earlier work of Murray (1965b) and shows that storm-induced transportation of foraminifera is a possible method of dispersal and re-colonization of environments after disturbance. Such transport of benthic foraminifera may also have the effect of mixing benthic assemblages and, thereby, confusing potential palaeoecological interpretations. It was anticipated that some propagules (sensu Alve and Goldstein, 2002, 2003, 2010, 2014), or tiny 1-2 chambered foraminifera, might have been recorded but none have been identified thus far. Clearly, if propagules could be dispersed in this way, then this method of dispersal would be all the more effective. Some of the specimens appear to contain sediment, indicating that these individuals had been picked up from the sea floor (despite their greater weight) and transported into the area of L4.

Footnote

During the summer of 2016, collection of plankton net samples by PML continued on a weekly basis and, in some cases, recorded benthic foraminifera. As these were not attributable to storm events, it is possible that some of these occurrences can be linked to rainfall events and the increased flow of water from the area of Plymouth Sound. On the 19th and 20th of November, 2016, the first winter storm (***Angus***) affected the area of L4 and there was a noticeable increase in benthic foraminifera in a sample collected on the 22nd November, 2016. Plankton samples continue to be collected weekly and it is hoped that each storm event during winter 2016–2017 will be monitored for the occurrence of transported benthic foraminifera.

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Foraminifera mentioned in the text (non-taxonomic order) with comments on their known occurrence in the local area

Amphicoryna scalaris (Batsch) = *Nautilus (Orthoceras) scalaris* Batsch, 1791, pp. 1, 4, pl. 2, fig. 4a, b: a relatively rare species off-shore Cornwall and in the Celtic Sea (Murray, 1971).

Asterigerinata mamilla (Williamson) = *Rotalina mamilla* Williamson, 1858, p. 54, pl. 4, figs 109–111: a common species offshore Plymouth and Cornwall which Murray (1971) records as being near to its northern limit.

Brizalina pseudopunctata (Hoeglund) = *Bolivina pseudopunctata* Hoeglund, 1947, pp. 273–274, pl. 24, fig. 5a, b, pl. 32, figs 23, 24, text-figs 280, 281, 287: this species is known from the English Channel (Murray, 1970) and was also recorded by Murray (1965b) in plankton tows collected after storms.

Brizalina spathulata (Williamson) = *Textularia variabilis* Williamson var. *spathulata* Williamson, 1858, p. 76, pl. 6, figs 164, 165. Murray (1970) records this species as living off-shore Plymouth and off the south coast of Cornwall in water depths of 10–42 m.

Bulimina elongata d'Orbigny, 1846, p. 187, pl. 11, figs 19, 20: a species that was initially described from the Vienna Basin. This Cenozoic species appears to be a plexus with *Bulimina gibba* Fornasini, though some authors prefer to use only the name of the extant form. A well-known plexus that is found along the English Channel Coast of South West England (Murray, 1965a, 1971).

Bulimina gibba Fornasini, 1902, p. 378, pl. O, figs 32, 34: see comments above.

Cibicides lobatulus (Walker & Jacob) = *Nautilus lobatulus* Walker and Jacob, 1798, p. 642, pl. 14, fig. 36: a cosmopolitan species offshore North West Europe that is known to live clinging to algae, shells and other substrates.

Cyclogyra sp. cf. *C. involvens* (Reuss) = *Operculina involvens* Reuss, 1850, p. 370, pl. 46, fig. 20a,b. Murray (1970) has recorded this species as living off Plymouth and the south coast of Cornwall in water depths of 10–60 m. It was also one of the species that Murray (1965b) recorded in plankton tows.

Eggerella scabra (Williamson) = *Bulimina scabra* Williamson, 1858, p. 65, pl. 5, figs 136, 137: a species with an initial trochospiral growth pattern, although this is often difficult to see under a light microscope. This is a common taxon around South West England.

Elphidium crispum (Linnaeus) = *Nautilus crispus* Linnaeus, 1758, *Systema Naturæ*, Ed. 10, Holmiae, p. 709: a species with a distinctive appearance, although the presence/absence of peripheral spines is extremely variable in populations around South West England.

Fissurina sp. cf. *F. lucida* (Williamson) = *Entosolenia marginata* (Montagu) var. *lucida* Williamson, 1848, pp. 17–18, pl. 2, fig. 7: Murray (1970) has recorded this species living off the south coast of Cornwall (14–42 m water depth) and in the samples collected after storms. The entosolenian tube is quite prominent, though not normally seen in SEM images (e.g., Murray, 1971, pl. 39).

Gavelinopsis praegeri (Heron-Allen and Earland) = *Discorbina praegeri* Heron-Allen and Earland, 1913, p. 122, pl. 10, figs 8–10: a shelf species that is well-known offshore South West England and which Murray (1965a, 1971) has recorded living offshore Plymouth.

Glabratella millettii (Wright) = *Discorbina millettii* Wright, 1911, p. 13, pl. 2, Figs 14–17: this species is recorded as both dead and living off the south coast of Cornwall by Murray (1970, 1971).

Globulina sp. cf. *G. gibba* d'Orbigny (as *Polymorphina (Globuline) gibba*), 1826, p. 266: a very variable, globular, species that has been recorded in both non-fistulose and fistulose form. It has been recorded as living offshore Plymouth by Murray (1965a).

Lagena perlucida (Montagu) = *Vermiculum perlucidum* Montagu, 1803, p. 525, pl. 14, fig. 3: this species is often seen to have a slightly 'twisted' ornamentation of the long neck. Murray (1971) records it as rare in the English Channel.

Massilina secans (d'Orbigny) = *Quinqueloculina secans* d'Orbigny, 1826, p. 303: a stenohaline form that Murray (1965a) has recorded living offshore Plymouth.

Oolina hexagona (Williamson) = *Entosolenia squamosa* (Montagu) var. *hexagona* Williamson, 1858, p. 13, pl. 1, fig. 32: an easily identified form with a characteristic ornament that has been recorded living offshore Plymouth (Murray, 1965a).

Parafissurina malcomsonii (Wright) = *Lagena laevigata* (Reuss) var. *malcomsoni* Wright, 1911, p. 4, pl. 1, figs 1, 2: a unilocular test with an entosolenian tube (only seen in light micrographs) that is known to live offshore Plymouth (Murray, 1965a).

Patellina sp. cf. *P. corrugata* Williamson, 1858, p. 46, pl. 3, figs 86-89: this species has been recorded south of Plymouth in 10–60 m water depth (Murray, 1965a) and in the English Channel south of the Lizard (Murray, 1970).

Planorbulina mediterranensis d'Orbigny,1826, p. 280. Pl. 14, figs 4–6: an inner shelf species that attaches to algae and shells using its flat, spiral side. It is well known, both living and dead, offshore Plymouth.

Quinqueloculina seminulum (Linnaeus) = *Serpula seminulum* Linnaeus, 1758, *Systema Naturæ*, Ed. 10, Holmiae, v. 1, p. 786: a typical inner shelf species around South-West England.

Textularia sagtitula Defrance, 1824, in Blainville, *Mollusques, Vers, et Zoophytes, Dictionnaire des Sciences Naturelles*, Paris, France, v. 32, p. 177, pl. 13, fig.5, 5a: a complex 'group' of highly variable forms that are well known in the shelf seas around the U.K.