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# Re-colonization of hostile environments by benthic foraminifera: an example from Montserrat, Lesser Antilles Volcanic Arc

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**ABSTRACT:** The Soufrière Hills Volcano, on the island of Montserrat, has an eruption history spanning over 2 million years. During this time the volcano has undergone multiple eruptions with intervening periods of low activity or dormancy. The most recent activity began in 1995 and has seen a series of major eruptive events. One of the most recent of these, and the focus of this study, occurred on the 20<sup>th</sup> May 2006. This major dome collapse produced 90 million m<sup>3</sup> of volcanic material in only 3 hours, propelling ash clouds through the air and pyroclastic flows down the side of the volcano and into the sea.

In this study of benthic foraminifera, cores from four sites off-shore Montserrat are analysed, including those collected from a location within the path of the 2006 ash cloud, around 10 km west of the Montserrat coast. In this area, one core contained 6–7 cm of ash overlying hemipelagic sediments. Volcanic ash is present in two distinct layers, one 3 cm layer produced by the 2006 eruption and the other, 3–4 cm layer, from an earlier eruption in 2003. Other cores were collected from areas unaffected by recent ash fall deposits and provide a base line for comparisons within the affected areas. To the east and south-east of Montserrat there is a different situation as this is the direction of travel of massive pyroclastic flows down the Tar Valley and the impact on the sea floor is more dramatic. There are also two extinct volcanic centres that allow the investigation of sea floor re-colonization on different time scales. The sites to the west of Montserrat record rapid colonization by benthic foraminifera of opportunistic taxa, comparable to that seen near Mt Pinatubo in the South China Sea while the sites to the east record a slower pattern of re-colonization by a wider spectrum of taxa, similar to that recorded at Deception Island in the Southern Ocean, with different benthic taxa performing the pioneering role.

**Keywords:** Montserrat, benthic foraminifera, Soufrière Hills Volcano, recovery patterns

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## INTRODUCTION

The foraminifera living in marine ecosystems are subjected to environmental change from a range of natural and anthropogenic occurrences. These are listed here, although this is more illustrative than exhaustive.

**1. Natural processes** include storms, tsunamis, turbidity currents, iceberg ploughing, aerobic/dysaerobic/anoxic changes, volcanic activity, etc.

**2. Anthropogenic processes** include sewerage spills, oil rig activities, marine dredging, coastal engineering, pollution from local catchments, mining waste ‘events’, etc.

Near-shore or estuarine foraminifera are most frequently subjected to pollution events, chemical spills, sewerage discharge and coastal engineering works. The impacts of pollution, and recovery from it, have frequently been described and there is a body of literature on such events and the occurrence of foraminifera with test abnormalities or unusual chemical contamination (*e.g.*, Sharifi et al. 1991; Stouff et al. 1999;

Olugbode et al. 2005; Bergamin et al. 2016; Skirbekk et al. 2016; Hart et al. 2020).

In deeper water ecosystems there is a growing awareness of the impact on the benthic foraminifera as a result of disturbance: a subject reviewed by Alve (1999). It is also known that assemblages of foraminifera can be disturbed around drilling platforms and oil wells (Jorissen et al. 2009; Denoyelle et al. 2010; Hess et al. 2013; Aagaard-Sørensen et al. 2016) and natural gas escapes (Rathburn et al. 2003; Dias et al. 2010; Consolaro et al. 2015; Burkett et al. 2018). The repeated disturbance of the sea floor by turbidity currents, especially in submarine canyons, also creates hostile conditions in which the recovery of assemblages of foraminifera is often disrupted by the next event. Indeed, as shown by Hess et al. (2005), such environments are often seen to be in a permanent state of ‘recovery’. Storms in which the wave base intersects the sea floor can also cause disturbance on an intermittent basis, with greater or lesser impact on the assemblages living in such locations (Murray 1965; Murray et al. 1982; Hart et al. 2017).

Volcanic activity, and recovery from it, has been described from two areas in the marine environment subject to recent eruptions, although the impact of ancient volcanic activity has also been described by Galeotti et al. (2002) and Wałkowska (2011). The two modern examples, that are more comparable with Montserrat, are:

1. The 1967–1970 eruptions on Deception Island in the Southern Ocean (Geyer et al. 2021), the recovery from which has been documented by Finger and Lipps (1981) and Gray et al. (2003); and
2. The eruption of Mt Pinatubo in the South China Sea in 1991 and the investigation of the foraminifera by Hess and Kuhnt (1996), Fisher (1999, unpublished thesis), Hess et al. (2001) and Kuhnt et al. (2005).

The research presented here focuses on the repeated eruptions of the Soufrière Hills Volcano on the island of Montserrat (Lesser Antilles Volcanic Arc), activity which is well-documented on the website of the Montserrat Volcano Observatory (MVO, [www.mvo.ms](http://www.mvo.ms)).

## GEOLOGICAL SETTING

The island of Montserrat (16°45'N, 62°10'W) is situated towards the northern end of the Lesser Antilles volcanic island arc (text-fig. 1). Created by the subduction of the North American Plate beneath the Caribbean Plate, the volcanic arc is 800 km long and splits into two groups of islands north of Martinique (Le Friant et al. 2004, 2008). The outer group of islands is older, consisting of a chain of extinct volcanoes that now have thick carbonate platforms covering the volcanic basement. The volcanic rocks of the inner arc are relatively much younger (~20 Ma) than those of the outer arc which are ~40 Ma (Le Friant et al. 2008) in age.

The island of Montserrat is 16 km long and 10 km wide and comprised exclusively of volcanic rocks (Le Friant et al. 2004). The island is formed of three volcanic centres: Silver Hills in the north; Centre Hills; and the South Soufrière Hills-Soufrière Hills complex (Le Friant et al. 2004) in the south. Pyroclastic deposits (predominantly ash fall and the results of pyroclastic flows) originating from the Soufrière Hills volcanic centre will be the focus of this investigation.

## Volcanic history

The island of Montserrat has a volcanic history spanning over 2 million years (Le Friant et al. 2004). Lava flows on the island date the Soufrière Hills Volcano back 170 ka (Le Friant et al. 2004), although recent work by Le Friant et al. (2008) shows that this volcanic centre may be significantly older. Tephra layers in marine sediment cores collected off the Montserrat coast, record the volcanic history of the South Soufrière Hills-Soufrière Hills Volcano back to 250 ka (Le Friant et al. 2008; Wall-Palmer et al. 2014, figs 10, 11 and references therein; Fraass et al. 2017). Over this time, the volcano has recorded multiple eruptions with intervening periods of low activity or dormancy (Le Friant et al. 2008). The most recent phase of eruption, which began in 1995 (Trofimovs et al. 2006), has seen the Soufrière Hills Volcano undergo a number of dome growth and collapse events (Montserrat Volcano Observatory; [www.mvo.ms](http://www.mvo.ms)). Much of the pyroclastic material produced during this time has been deposited in the ocean around Montserrat (text-fig. 2). Trofimovs et al. (2006) suggested that, since 1995,

more than 90% of eruptive material produced by the volcano has entered the ocean. This has occurred largely through the action of sub-marine pyroclastic flows, lahars and, to a lesser extent, through airborne ash fall-out. On 12<sup>th</sup>–13<sup>th</sup> July 2003, the Soufrière Hills Volcano produced the largest documented historic dome collapse of any volcano (Trofimovs et al. 2006; MVO, [www.mvo.ms](http://www.mvo.ms)). The remnants of the volcano and the devastation of Plymouth can be seen in text-figure 3. This occurred over a period of 18 hours, yielding  $210 \times 10^6 \text{ m}^3$  of pyroclastic material (Herd et al. 2005). Since this major collapse, there has been further activity and, on the 20<sup>th</sup> May 2006, another major dome collapse occurred. This collapse occupied a much shorter interval of time (3 hours) and produced around  $90 \times 10^6 \text{ m}^3$  of material (MVO, [www.mvo.ms](http://www.mvo.ms)). Although less material was produced during this rapid eruption, the increased momentum propelled pyroclastic flows much further into the marine environment. The volcano continues to be very active and the Soufrière Hills Volcano has undergone a series of partial dome collapse events (e.g., July–August 2008, December–January 2009, January–February 2010 and June–July 2010, after which it has been relatively quiescent).

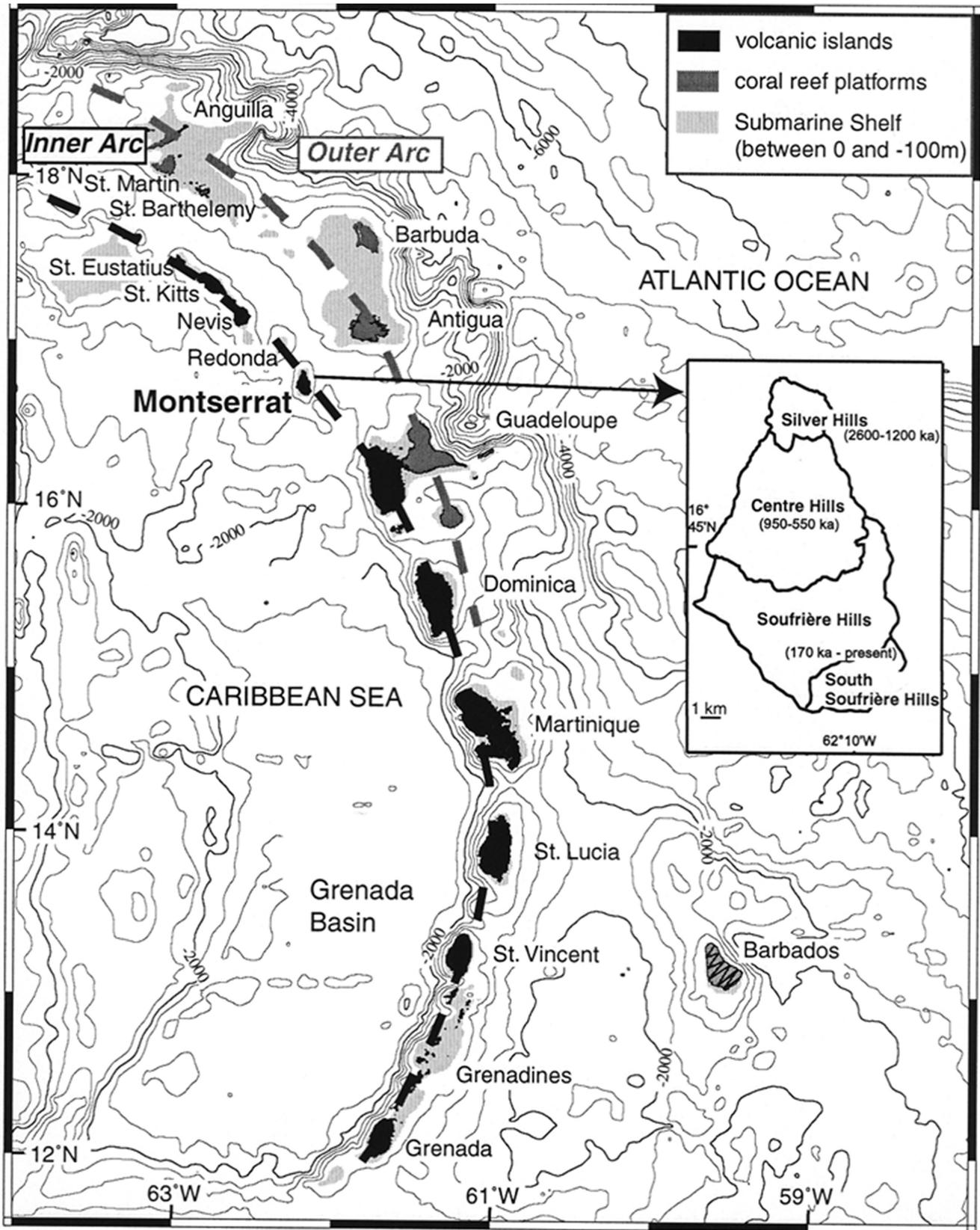
Whilst most pyroclastic flows travel to the south-east of the island, down the Tar Valley and into the ocean (Hart et al. 2004; Trofimovs et al. 2006), it is evident that ash clouds produced during eruptions of the Soufrière Hills volcano are transported by north-easterly Trade Winds (text-fig. 2). Ash fall events, therefore, affect this area and cores taken from close to the path of the ash clouds have been analysed during this investigation. Closer to shore, a number of major lahars have entered the ocean by way of the Belham Valley, located just to the north of the ruined town of Plymouth (the island's former 'capital').

## Volcanic events relating to this investigation

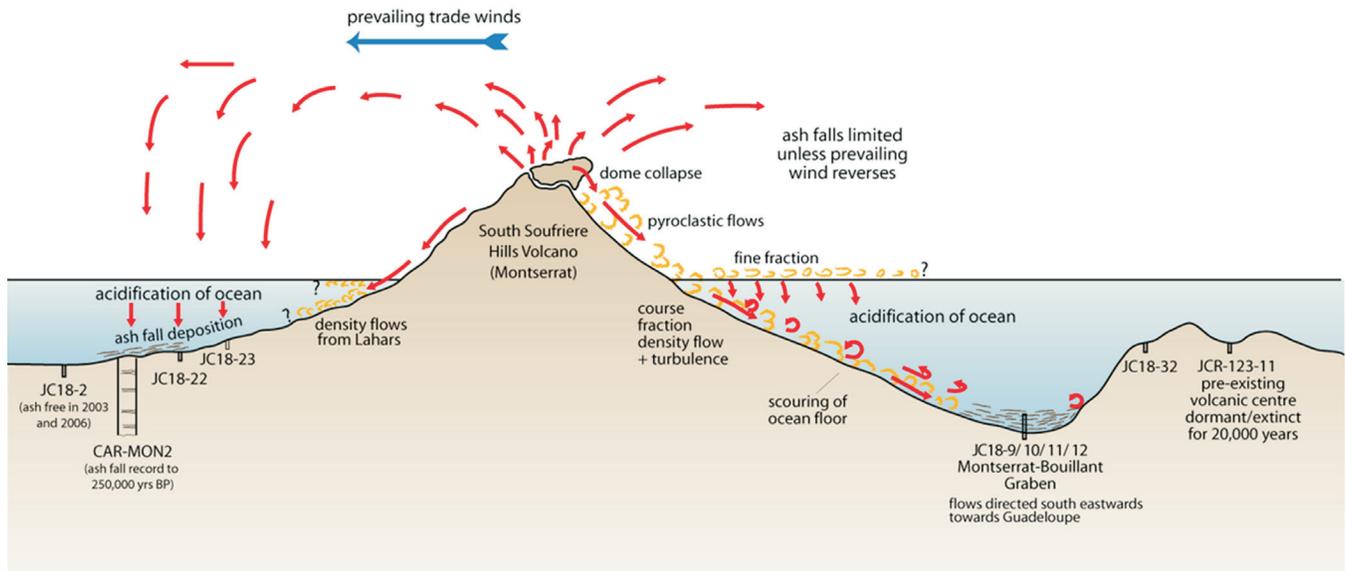
In July 2003, after an eight-year period of dome growth and collapse events, the Soufrière Hills Volcano erupted to produce the largest documented historic dome collapse of any volcano (Trofimovs et al. 2006). Two hundred and ten million  $\text{m}^3$  of erupted material covered the Montserrat area, much of it entering the sea. In the waters around Montserrat, the benthic marine assemblages (including the foraminifera) were smothered and, in many areas, decimated. Following this major eruption, a further major dome collapse occurred on 20<sup>th</sup> May 2006. This also smothered a large area of the island and surrounding ocean with 90 million  $\text{m}^3$  of volcanic material. In the affected areas, any benthic community recovering after the 2003 event would almost certainly have been impacted, returning the cycle of recolonization back to the beginning. It is these periodic eruptions of the Soufrière Hills Volcano that provides a unique opportunity to observe the effects of volcanic disturbances on assemblages of benthic foraminifera within an accurate, well-documented, time scale.

## RE-COLONIZATION BY BENTHIC FORAMINIFERA

In recent years, there have been several studies of the re-colonization of deep-sea substrates following catastrophic environmental disturbances within the fossil record: for reviews on this subject see Alve (1999), Galeotti et al. (2002), Wałkowska (2011) and Di Bella et al. (2015). These accounts have provided information regarding the extent to which individual events have altered the environment and the approximate time periods required for their recovery. Most re-colonization studies within the modern oceans have, however, mainly concentrated on recovery in shallow water areas (Schafer 1982; Ellison and Peck



TEXT-FIGURE 1  
 Location of Montserrat within the Lesser Antilles Volcanic Arc. Inset map shows the main volcanic areas of Montserrat and their relative ages; after Le Friant et al. (2008).



TEXT-FIGURE 2  
Schematic model for the distribution of volcanic deposits around Montserrat.

1983; Alve 1995). Very few studies have been made of disturbances in deeper water environments and even fewer have been made of volcanic disturbances.

The first major study of disturbance to deep-sea environments was carried out by Kaminski (1985). This investigated the effect on agglutinated foraminifera of ‘benthic storms’ in deep water (~4000 m) caused by intense contour currents in the North Atlantic Ocean events and considered the differences between disturbed and undisturbed assemblages. Kaminski (1985) found that disturbances created assemblages with increased numbers of opportunistic species and lower species diversity when compared to an undisturbed area. More recently work by Hess et al. (2005) investigated the re-colonization of benthic foraminifera following turbidite deposition in the Bay of Biscay. This study of an extremely unstable environment showed that the foraminiferal assemblage in this location was in a constant state of renewal. Hess et al. (2005) found that the community structure permanently remains in an early stage of re-colonization and that recovery from complete devastation to this early stage takes only 6 to 9 months.

In the modern ocean, there are only three geographical areas that have been studied for re-colonization by benthic foraminifera following volcanic eruptions. The first, undertaken by Finger and Lipps (1981), monitored the decimation of the benthic foraminifera and the re-population of an active volcanic caldera on Deception Island (Geyer et al. 2021, and references therein) in the Southern Ocean. That study took place over five years and clearly shows patterns in re-colonization, although the follow-up research by Gray et al. (2003) has indicated that the earlier trends have changed slightly over time. The second, in the South China Sea, studied the aftermath of the 1991 eruption of Mt Pinatubo, and includes a series of analyses

by Hess and Kuhnt (1996), Fisher (1999), Hess et al. (2001) and Kuhnt et al. (2005). All these studies describe differences in the style and timing of re-colonization, with Gray et al. (2003) questioning the relative importance of the various species involved in the process. The third area is that of the Azores, where Di Bella et al. (2015) have described the foraminiferal assemblages in an area with active volcanism.

It is widely reported that, in areas that have only experienced a thin covering of volcanic sediment (15–25 mm thick), the foraminiferal assemblages are not destroyed completely. Hess et al. (2001) found that whilst most detritivores, tubular agglutinated species and epifaunal and sessile suspension feeders were reduced in numbers, infaunal and mobile species were able to survive the disturbance. The assemblages of these areas remained largely the same as the pre-ash fall community but with decreased abundance (Hess et al. 2001). The pre-ash fall steady state was regained through immigration from nearby unaffected areas that gradually replenished the community though, since that time, the dispersal of foraminifera by means of ‘propagules’ (Alve and Goldstein 2002; 2003; 2010; 2014; Goldstein and Alve 2011) is now recognized as potentially being of greater importance.

Areas covered by a thicker layer of volcanic material were found to be more seriously affected suffering a loss of most, if not all, the benthic assemblage (Hess et al. 2001). The initial study of the Mt Pinatubo ash layer carried out by Hess and Kuhnt (1996) showed that even after three years, re-colonization was only in its early stages and that the community was far from recovered. This long recovery is due to the source of the re-colonizing species. Whereas an area at the edge of the ash deposit may be re-populated from the adjacent, unaffected areas, it is not possible for immigrant species to migrate into the central



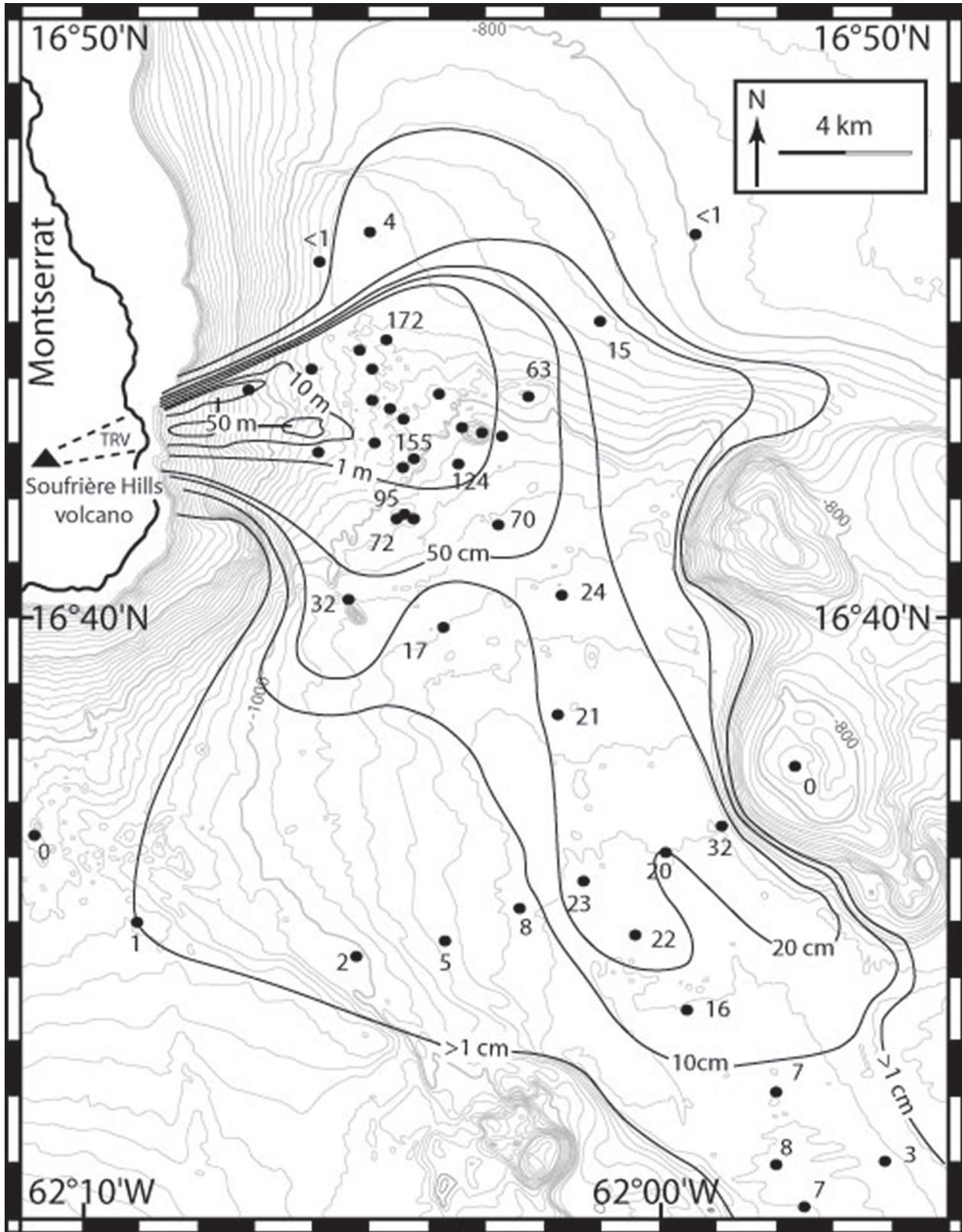
TEXT-FIGURE 3

The ruins of Plymouth (in May 2005), with the Soufrière Hills volcanic centre in the distance. The ‘gap’ in the crater was caused by the explosive nature of the 2003 eruption.

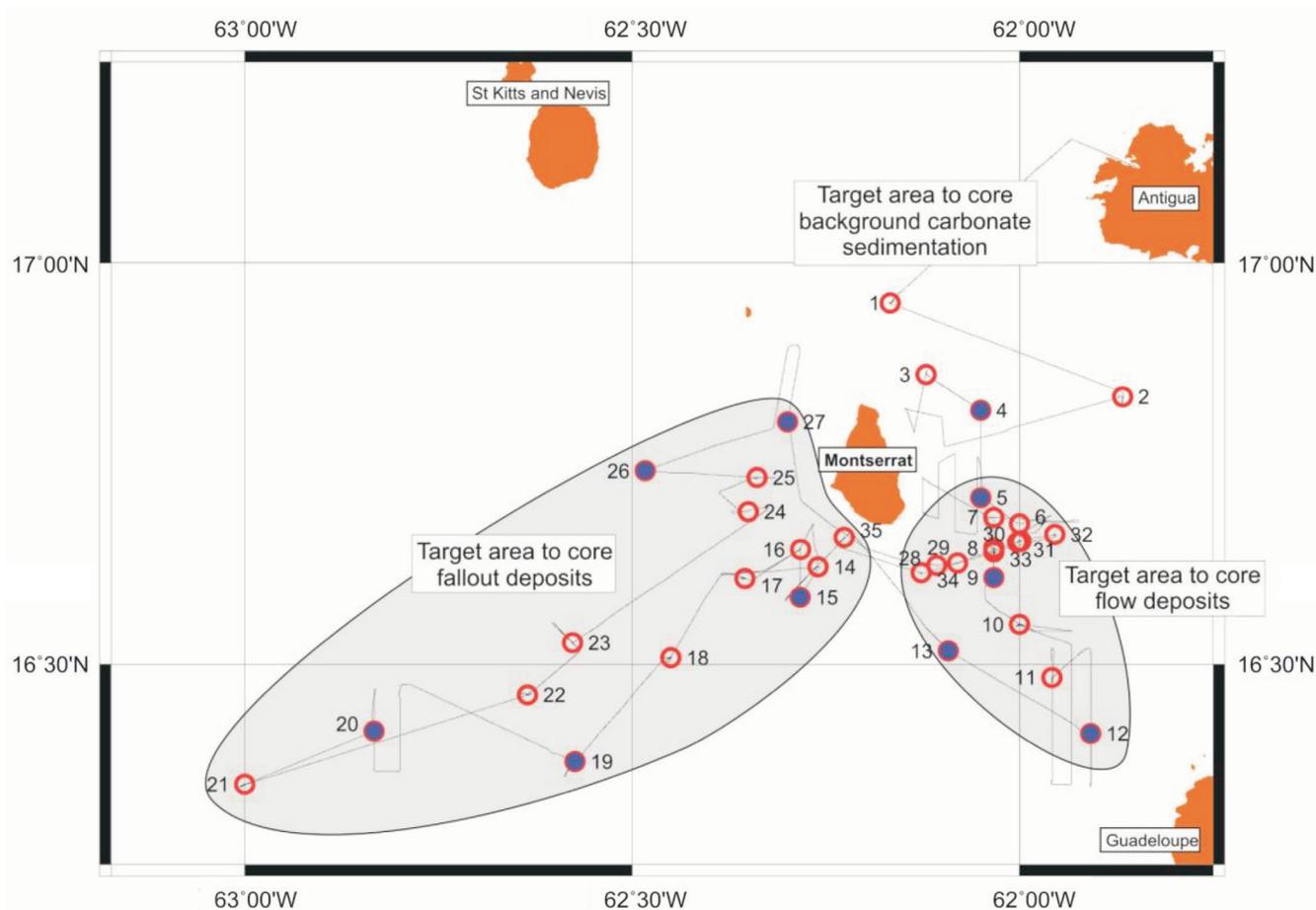
parts of the ash deposit from such a great distance (Hess et al. 2001). This idea is supported by the discovery that most of the pioneering and successive re-colonizing species observed from the thicker parts of the Mt Pinatubo ash layer were not present in the pre-ash fall community or the surrounding, unaffected, areas (Hess and Kuhnt 1996). Another explanation for this relatively slow re-colonization is the coarse grain size of the ash deposit. The coarse, well-sorted characteristics of the ash make it difficult for benthic foraminifera to burrow and move through the layer (Hess et al. 2001). Kitazato (1995) investigated the preferences of benthic foraminifera in re-colonizing different substrates and found that the barren sediment was re-colonized by both shallow and deep burrowing infaunal species. Over the same time period, a substrate of minute glass beads (similar to ash grains) was only re-colonized by shallow burrowing infaunal species within the newly deposited layer of ‘fluff’ on the surface: they did not penetrate the sediment of beads. Ship-board observations of several cores recovered during cruise JC18 of the RRS *James Cook* (in December 2007) also suggest that, in some areas such as the Bouillante–Montserrat Graben (text-figs 4, 5), the volcanic sediment from some earlier

eruptions has not yet settled, creating a substantial layer (<2 m) of water-logged, thixotropic sediment that would be impossible for any organisms to re-colonize. The cores used in this study, however, did not contain any evidence of this ‘fluid’ sediment as these sites were impossible to sample. Hess et al. (2001) observed that once burrowing activity does occur, it subsequently creates new ecological niches for more specialized foraminifera. In this way, the diversity of the recovering assemblage is gradually increased.

Benthic foraminifera can be grouped into two types, K- and r-strategists, the proportions of which represent responses to different types of environment (MacArthur and Wilson 1967). The r-strategists, being the first to recolonize following a major disturbance, are opportunistic and take advantage of the lack of predation. They are characterized by the capability of rapid dispersion, high reproduction rates and relatively short life cycles. They consist mainly of mobile, infaunal detritivores with typical representatives including *Reophax* spp., *Textularia* spp., and *Ammobaculites* spp. (Fisher 1999; Hess et al. 2001). Over time, these species produce niches which increase the opportunities



TEXT-FIGURE 4  
 Sites drilled by the RRS *James Clarke Ross* in May 2005 during Cruise JCR123 allowed the reconstruction of an isopachyte map showing the thickness of volcanic sediments to the east and south-east of Montserrat (including the Bouillante-Montserrat Graben (towards Guadeloupe)). Contours are shown in meters and, where volcanic sediments are thinner, in centimeters. The two extinct volcanic centres (Kahouanne volcanoes) to the east of the graben are shown to have received almost no volcanoclastic sediments; see text for discussion. Map based on work of Trofimovs et al. (2006).



TEXT-FIGURE 5

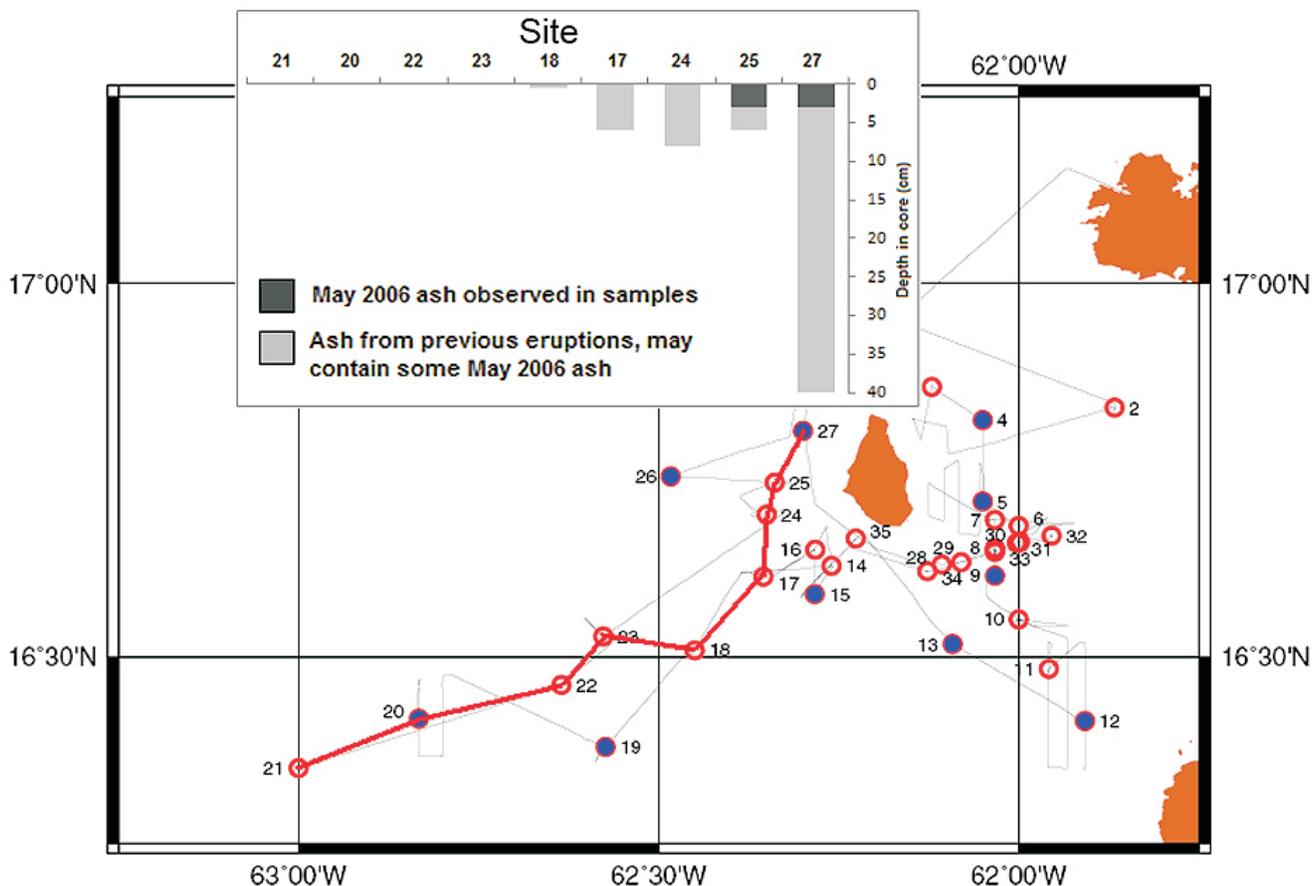
Target sites for Cruise JC18, including the areas to the west and south-west of Montserrat and the sites drilled to the south-east of Montserrat in the Bouillante-Montserrat Graben (towards Guadeloupe). Site 18-32M is located on the flank of a former volcanic centre that is located to the east of the graben.

for other taxa. With this, however, competition and predation are also increased. The first colonizers are gradually replaced by a second succession, with the K-strategists flourishing in the less stressed, more stable environment. In such an environment, qualities found in the r-strategists, such as a rapid reproduction rate, are less beneficial and the competitive skills found in the K-strategists become more favoured.

Fisher (1999) has described a typical re-colonization pattern. Firstly, the lack of competition in the barren sediments enables opportunistic species (r-strategists) to grow at an exponential rate, their numbers often higher than those of the pre-disturbance population. This continues until an increase in competition and a decline in resources causes a reduction in the pioneer species, making way for the more specialized species (Ellison and Peck 1983; Fisher 1999). Continuous disturbance however, such as the periodic eruption of a volcano, will re-set this process back to the beginning, so that in some systems, the second wave of succession may never happen. An example of this was reported by Hess et al. (2005), describing the near-continuous, periodic turbidite deposition in the Cap Breton Canyon that has created a foraminiferal community that remains almost permanently in an early stage of re-colonization.

On the sea floor near to Mt Pinatubo, signs of initial re-colonization occurred over three years from the volcanic disturbance (Hess et al. 2001). Alve (1999), however, suggests that recovery of disturbed areas may take as little as a year although the accuracy of such predictions can often be a function of sampling schedules. In the case of deep-sea locations, return visits to sampling sites may, of necessity, be several years apart.

The extent of the re-colonization following the 2006 eruption is not known since the JC18 sampling expedition in December 2007. It can be shown, however, that there was some recovery after the 2003 eruption, and before the 2006 eruption. The understanding of this is, of course, a function of the regularity of sampling, with the JC18 cruise (in December 2007) taking place only ~18 months after the May 2006 eruption. It must be noted that to the east of the Soufrière Hills volcano, pyroclastic flows have almost destroyed the normal sea floor environment and this has limited the assessment of the re-colonization assemblages in that area. To the west of Montserrat, however, the 2006 deposits were predominantly created by ash fall, with some lahar deposits only in near-shore areas. These ash-fall deposits are much less erosive and the assemblage that has re-colonized the 2003 ash is, therefore, preserved below the more recent ash fall event.



TEXT-FIGURE 6  
The thicknesses of ash in the JC18 cores drilled to the south-west of Montserrat. This profile shows the relative positions of JC18-21M and JC18-25M.

**MATERIAL AND METHODS**

Marine sampling in shallow to moderate water depths can employ a range of equipment and techniques and in the marine environment off-shore Montserrat, the following methods have been used with variable success. All the samples collected for the analysis of the foraminifera and other microfossils (e.g., holoplanktonic gastropods) are identified by the cruise (or name), site number and type of core (e.g., V = vibrocore, M = megacore, etc.).

Vibrocoreing is a method for the collection of continuous, undisturbed cores of unconsolidated, loosely compacted or even semi-lithified sediments by driving a tube with a vibrating device that is usually mounted on a tripod or frame that is lowered to the sea floor. The sediment is held in a plastic lining tube with a spring-loaded device that allows sediment to enter the tube but not fall out during recovery.

The term ‘megacore’ is used here for one of the sample tubes collected by a multicorer device that is lowered onto the sea floor after which the individual core tubes are pushed into the upper sediment layers.

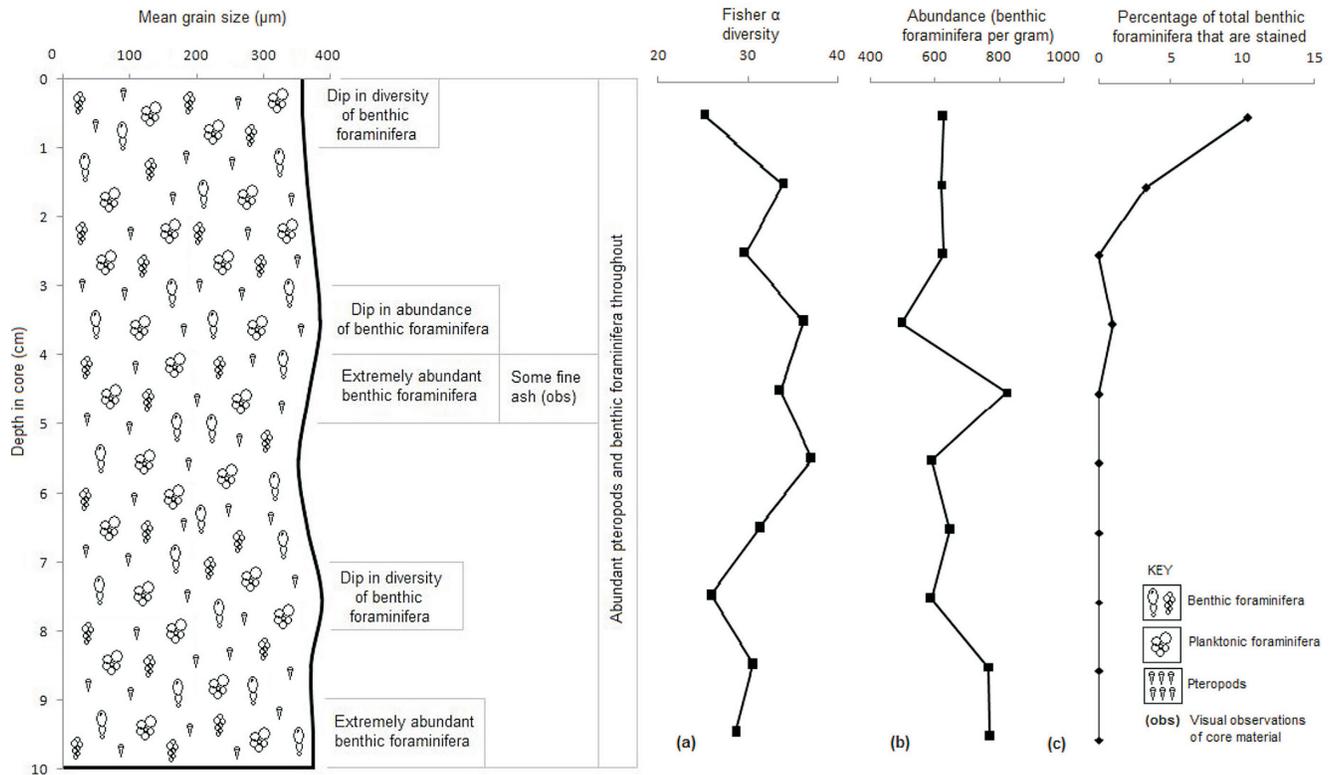
The gravity or piston core consists of a core barrel with plastic liner that is lowered to a position just above the sea floor at which point it is ‘dropped’ into the sediment. In the case of a

piston core an additional weight is released to give better penetration of the sediment. Piston coring was used on the ‘Caraval’ cruise of the RV *Atalante* in 2002 and provided the cores (CAR-MON 1, 2, 3 and 4) used by Le Friant et al. (2008) in their analysis of the eruption history of the Soufrière Hills volcano.

The box core is one of the simplest, and most commonly used, sediment sampling devices. The steel box is usually ca. 50 cm x 50 cm x 75 cm and after dropping to the sea floor is closed by a steel plate that allows the sample to be retained. Though deployed on the JC18 cruise in 2007, the samples collected by the megacorer were regarded as better for microfossil analysis.

Dredge samples are collected in a wire basket that is dragged across the sea floor. Though deployed twice on the JC18 cruise (near the location of site JC18-32M) the collected samples were too imprecisely located for microfossil analysis.

In December 2007 a number of sediment core samples (for use in several studies) were collected from 35 sites off-shore Montserrat by the JC18 cruise of the RRS *James Cook* (text-figs 5, 6). These cores supplement those collected by the RV *Atalante* in 2002 (Le Friant et al. 2004; 2008) and a number of vibrocores collected in May 2005 by the RRS *James Clark Ross* on cruise JCR123.



TEXT-FIGURE 7  
Key features of core JC18-21M showing the absence of any ash-fall deposits and information on the nature of the foraminiferal assemblages.

**Megacore JC18-21M**

Megacore JC18-21M was collected from an area thought to be unaffected by ash-fall deposits or pyroclastic flows (text-figs 6, 7). The site is located ~100 km to the south west of the Montserrat coast (16°21'N, 63°00'W) in a water depth of 1270m. It was expected to contain a 'natural' assemblage of benthic foraminifera and, also, a 'natural' pteropod and planktic foraminifera assemblage of dead individuals unaffected by the volcanic deposits. As the prevailing winds often drive ash clouds towards the south west, this area may be slightly affected by distal ash fall, and this was checked during sample processing.

**Megacore JC18-25M**

Megacore JC18-25M was collected from an area off the west coast of Montserrat, around 10 km from the Soufrière Hills volcano (16°44'N, 62°20.31'W) in a water depth of 878 m. JC18-25M recorded 7cm of volcanic material in 2 layers; a 3 cm thick layer on the surface representing the 2006 eruption of the Soufrière Hills Volcano, while the additional 4 cm of ash below this layer was assumed to have been created by the 2003 eruption (text-figs 6, 8). In this area the assemblage of benthic foraminifera is assumed to have been completely destroyed by the 2006 layer of ash.

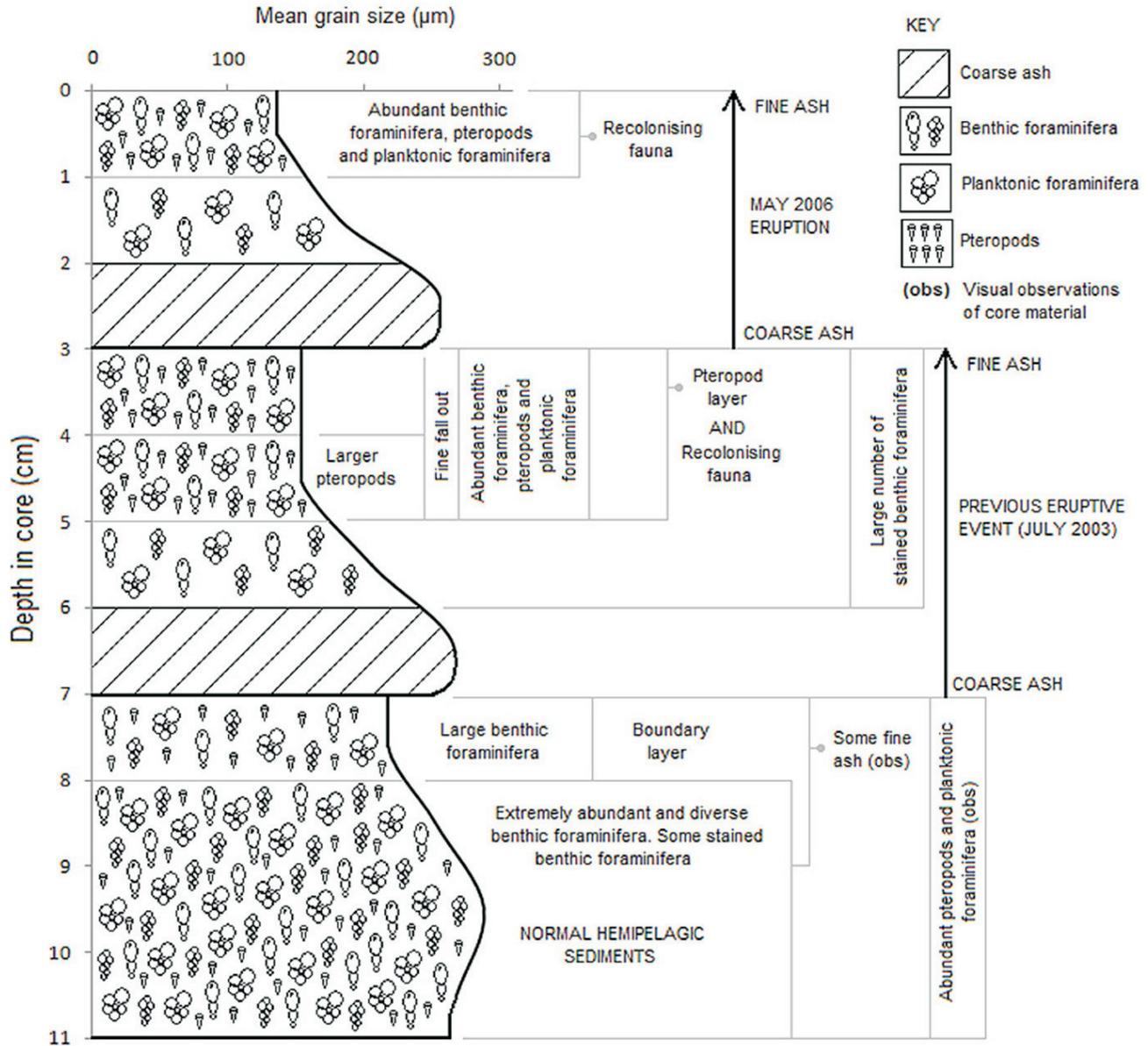
**Megacore JC18-32M**

Core JC18-32M was collected from an area of sea floor to the south east of Montserrat (16°39.70'N, 61°57.25'W) in a water depth of 876 m. The core was located on a sloping saddle be-

tween the extinct Kahouanne volcanoes (Trofimovs et al. 2013, text-fig. 1) on the east side of the Bouillante-Montserrat Trough and over 200 m above the surrounding sea floor (text-figs 4, 9). The location from which the core was taken was well away from the recorded direction of ash clouds but was in the region of sea floor affected by pyroclastic flows sourced from the Tar River Valley. The core was taken using a multicorer but during collection of the core it 'struck' a serpulid-encrusted limestone hardground at a depth of 16 cm and could not penetrate any further. Core JC18-32M recovered only ~16 cm of sediment (text-fig. 9) but records three separate volcanic events, each with erosive bases and a distinctive graded profile.

**Vibroc core JCR123-11V**

The site of JCR123-11V was located in one of the former 'craters' of the Kahouanne volcanoes to the south-east of Montserrat. This vibroc core recovered a thickness of hemipelagic sediments which grade downwards into black, basaltic ash. The drilling was eventually terminated in this ash, with no sign of a return to hemipelagic sediments. It was assumed that this represented the ash within the old crater as the thickness of ash was >115 cm. The transition from the ash to the overlying hemipelagic sediments, therefore, provides a record of the genuine onset of normal, carbonate-rich sedimentation following the end of volcanism at the site. None of the samples above this transition show any signs of volcanic sediment and the area appears to have escaped any further impact by volcanic ash, despite the presence of volcanic sediments in the nearby Bouillante-Montserrat Graben. The beige-colored, serpulid-en-



TEXT-FIGURE 8A  
Key features of core JC18-25M showing the presence of the two ashes from the 2003 and 2006 eruptions.

crusted limestone (described below) occurs within the carbonate succession (text-fig. 9).

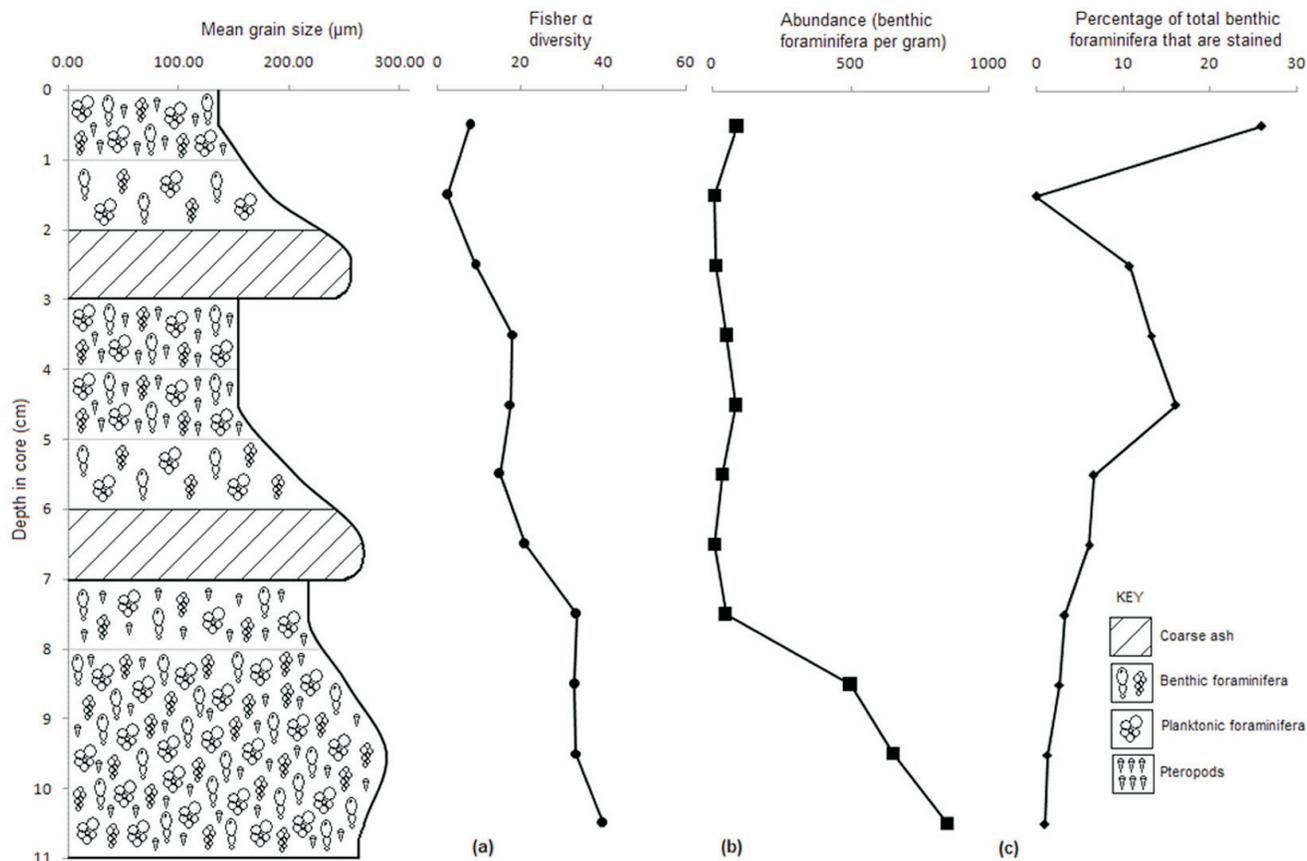
#### Preparation of samples from Megacores JC18-21M, JC18-25M and JC18-32M

These cores were collected using a multicorer which consists of up to twelve plastic tubes, 10cm in diameter, mounted within a metal frame. Using this method at each station, at least one core was collected as an archive and one was collected for micropaleontological analysis. The sea water was carefully siphoned off the core and the sediments were carefully extruded from the tube. As the core was extruded, 1 cm slices were taken. Some expansion of the sediments was observed but, to minimize any distortion, the cores were sliced as quickly and as ac-

curately as possible. Archive cores from the same stations were also logged to match the stratigraphy of the sampled cores.

For both cores, sample preparation was carried out immediately on-board the ship. The samples were cleaned of the sediment smeared by the extrusion process, placed in bowls and immersed in buffered formalin for 2 hours in order to fix any living protoplasm. The samples were then soaked in rose Bengal for a further 3 hours. All the samples were washed over a 63 μm sieve to remove any fine ash and sediment, filtered and air dried in the filter paper. Once dried, samples were placed into labelled plastic storage bottles for transit to the UK.

The authors are aware of the controversies that exist over the use of the rose Bengal stain for the identification of the 'living'



TEXT-FIGURE 8B  
Data on the nature of the foraminiferal assemblages.

assemblage (Walton 1952; Bernhard 1988, 2000; Murray and Bowser 2000; Schönfeld et al. 2012). Our use of 3 hours for the staining process is based on experience in South-West England whilst investigating modern assemblages in estuarine and near-shore marine settings (*e.g.*, Sadri et al. 2011).

The fine fraction (<63 µm) was not collected but visual inspection indicated that no ash was present at site JC18-21. Grain size analysis was carried out on the samples from the two cores prior to splitting for micropaleontological analysis. Each sample was split in half to provide a micropaleontological archive. The working half was then split in half to provide sufficient undisturbed sample for the analysis of both the foraminiferal assemblage and the pteropod fauna.

The grain size of the sediment was analysed to determine the position of volcanic deposits and the type of eruption that occurred to produce them. Grading was carried out using a stack of sieves, including 500 µm, 250 µm, 125 µm and 63 µm. The weight of each fraction was recorded and the mean grain size calculated in order to produce a sedimentological log of the cores.

To investigate the re-colonization of the ash deposits, benthic foraminifera were collected from the un-affected core (JC18-21M) to provide an indication of the ‘natural’ assemblage. This was then compared to the area affected by ash fall

deposits (JC18-25M). For cores JC18-21M and JC18-25M, samples were split into size fractions of 63-150 µm and >150 µm, enabling the results to be directly comparable to the results from Mt Pinatubo (Hess and Kuhnt 1996; Fisher 1999; Hess et al. 2001; Kuhnt et al. 2005). Just over 300 benthic foraminifera were counted from this fraction for each 1 cm sample. Each sample was weighed, before and after, picking to determine the number of benthic foraminifera per gram of sediment. Identification of species was made with the use of Gooday (1984), Jones (1994) and other recent papers on benthic re-colonization (Hess and Kuhnt 1996; Hess et al. 2001).

For most species, counted specimens must have retained their proloculus. Tubular agglutinated, and especially branching species are, however, extremely fragile and are prone to breakage. It is, therefore, difficult to know how many whole individuals these fragments represent and hence, for such species each fragment is counted as a specimen. This will introduce discrepancies in the results obtained and this must, therefore, be considered in any interpretation of the data.

Preservation of the microfossils in most of the investigated samples is excellent with the intricate structures and spines of radiolarians and planktic foraminifera largely undamaged and the ornamentation of many foraminifera still visible. The rose Bengal stain was also taken up by many of the foraminifera, which are presumed to have been alive at the time of collection: see

earlier comments and Schönfeld et al. (2012) for a discussion of the rose Bengal methodology.

The depth of ash resulting from numerous eruptions of the Soufrière Hills volcano was observed during sample preparation on board the RRS *James Cook*. The transect across the sites shows that, despite the explosive collapse events of 2003 and 2006, volcanic deposits do not extend very far out to the west and south-west (text-fig. 6). Volcanic deposits were recovered only as far as site JC18-18, which is approximately 35 km to the south west of the volcano. Sites JC18-23, JC18-22, JC18-21 and JC18-20 do not contain any volcanic ash, with only a fine (<0.5 cm) layer at site JC18-19. For the two sites containing volcanic material (JC18-27 and JC18-25), the depth of the 2006 deposit is known and was found to be 3 cm from observations during the analysis of samples. This sedimentological description (text-figs 7, 8) has been produced by using grain size analysis data as well as ship-board observations.

#### Preparation of samples from Vibrocore JCR123-11V

As the RRS *James Clarke Ross* has no micropaleontological processing facilities on board, samples from the cores were collected, placed in plastic storage jars with buffered formalin and returned to the UK. Once in the laboratory, the JCR123 samples were processed and studied using the methodology described above.

### ANALYSIS OF THE FORAMINIFERA

#### JC18-21M

Core JC18-21M consists exclusively of uniform hemipelagic sediments that show very little fluctuation in mean grain size (text-fig. 7). The diverse and abundant remains of pteropods (Messenger et al. 2010), planktic and benthic foraminifera are found throughout the core. During microfossil analysis, some fine ash was also observed at 4–5 cm in the core. The age of this ash layer is not known but can be estimated as being over 1,000 years old as this area of the Caribbean Sea has an average sedimentation rate of 3 cm per 1,000 years (Reid et al. 1996). The 10 cm of this core that has been studied may, therefore, represent over 3,000 years of sedimentation. The oxygen profile of core JC18-21M showed a progressive decrease of oxygen from 250  $\mu\text{mol/l}$  to around 0  $\mu\text{mol/l}$  in 2–7 cm of sediment (Hembury et al. 2012). This indicates that the sediments were well oxygenated at depth.

Throughout core JC18-21M, the assemblage of benthic foraminifera is abundant and diverse with Fisher  $\alpha$  index values ranging from 26.5 to 35 (text-fig. 7). On average, there were 655 benthic foraminifera per gram of sediment, a value that is consistent throughout the core. A total of one hundred and sixty-three species were recorded. In the surface three centimetres the assemblage is mainly composed of tubular and epifaunal forms (*Saccorhiza ramosa*, *Rhabdammina abyssorum*, *Rhizammina algaeformis*, *Cibicidoides wuellerstorfi* and *Cibicidoides robertsonianus*), typical of a low stressed, undisturbed area. Some infaunal detritivores and sessile suspension feeders are also present, including *Reophax* spp., *Globocassidulina subglobosa* and *Siphovigerina ampullacea*. The live assemblage is dominated by tubular forms such as *Saccorhiza ramosa* and epifaunal forms such as *Hoeglundina elegans* and *Cibicidoides* spp. Some live *Reophax* spp. were also present. The dead assemblage is dominated by similar forms, with the addition of *Reophax scorpiurus* and *Reophax*

*spiculifer*. Living benthic foraminifera were found to a depth of 3–4 cm (Table 1), which reflects the oxygenation of the sediments (Jones and Gislason 2008; Hembury et al. 2012).

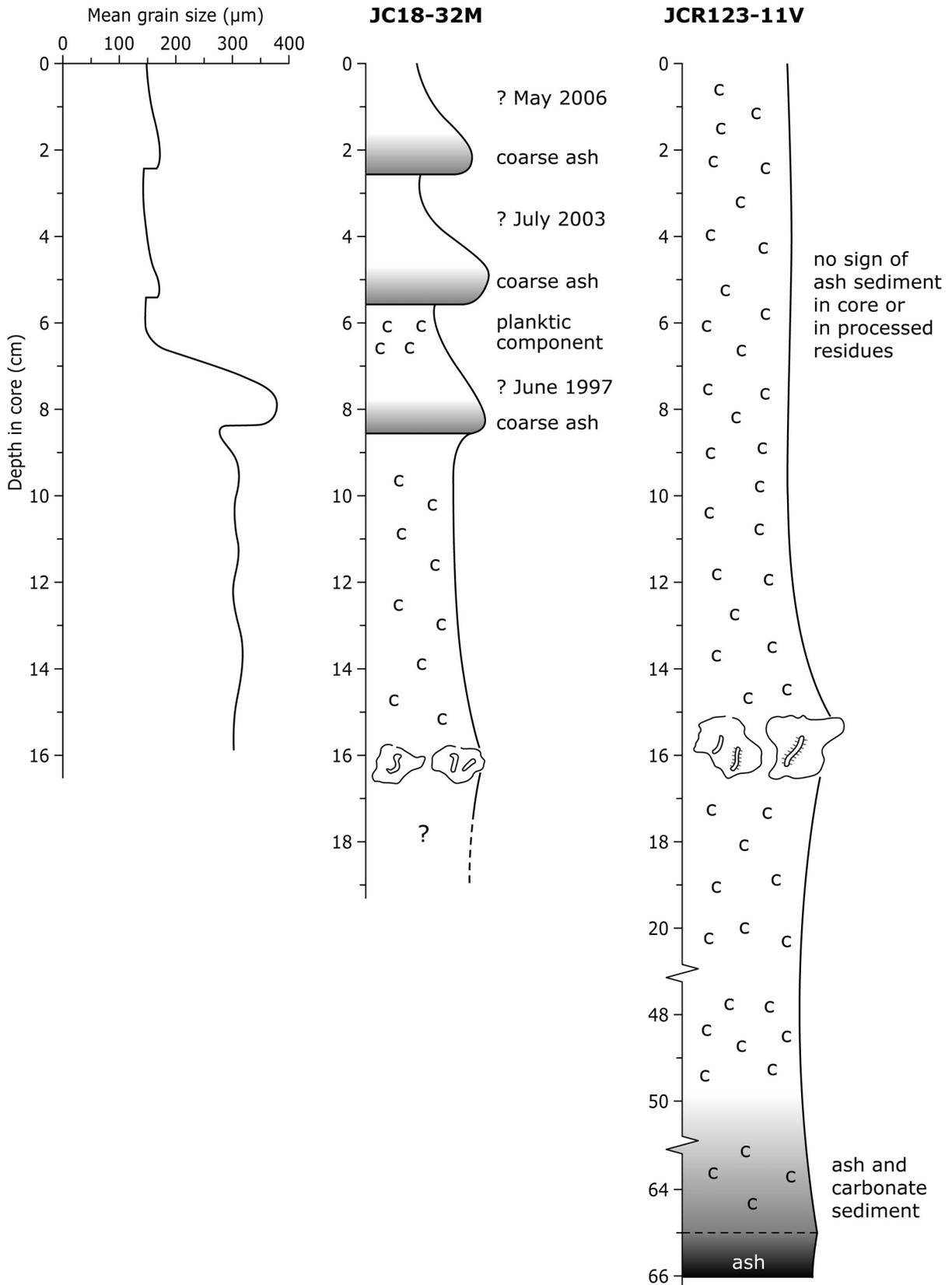
#### JC18-25M

Core JC18-25M contains 7 cm of volcanic material in two obvious layers, above 4 cm of normal hemipelagic sediment (text-figs. 8, 10; Table 1). The more recent layer of volcanic sediment is 3 cm thick. It is graded from coarse at the base to finer ash at the surface. The surface 1 cm, however, contains abundant holoplanktonic gastropods (pteropods and heteropods) and planktic foraminifera. It also contains an abundant and diverse assemblage of benthic foraminifera, several of which were stained by the rose Bengal. This layer represents both the re-colonizing benthic foraminifera in the surface layers of the volcanic deposit but also the beginnings of an accumulation of planktic taxa.

The older layer of volcanic sediment is 4 cm thick and graded from a coarse volcanic ash at the base to a fine ash near its upper surface. In the fine volcanic sediments at the top of the deposit (between 3–5 cm), there is an abundance of benthic foraminifera, planktic foraminifera and holoplanktonic gastropods. This represents the decimated planktic fauna (in addition to the naturally deposited planktic assemblage) and the re-colonizing benthic foraminifera. During the 2006 dome collapse, both ash clouds and lahar surges deposited volcanic material to the west of Montserrat and in some areas, therefore, two layers of volcanic material were produced by the 2006 eruption.

Between 7 and 8 cm, there is a boundary layer where remains from the hemipelagic sediment below are found in a lower abundance and fine volcanic ash is recorded. From here on, this sample will be included as part of the hemipelagic sediments found directly below it. From 8 cm to 11 cm, the core consists of only ash-free hemipelagic sediment. This sediment is of a relatively uniform grain size and is comparable to the hemipelagic sediment found in core JC18-21M. The oxygen profile of core JC18-25M showed a rapid decrease of oxygen in only 2 cm of sediment (see Hembury et al. 2012). Oxidation of the 2006 ash has removed oxygen from, and is preventing the replenishment of oxygen to, the underlying sediments.

At the surface of core JC18-25M (on top of the ash layer), the assemblage is mainly composed of epifaunal and infaunal detritivores, such as *Bulimina aculeata*, *Bolivina albatrossi*, *Veleroninoides jeffreysii* and *Trochammina inflata*. Some *Reophax* spp. and *Cibicides* spp. are also present. *B. aculeata* is the most abundant benthic foraminiferid in the surface 1 cm, making up 34% of the total assemblage. Of the surface three centimetres, the first (0–1 cm) contains the majority of live individuals (35). At 1–2 cm no live benthic foraminifera were found although, at 2–3 cm, they reappear again in low numbers (6 individuals). Live specimens of 14 species were found in the surface 1 cm sample. This live assemblage is dominated by *B. aculeata*, *Gyroidinoides soldanii* and *H. elegans*, which comprise 49% of the live assemblage in the surface 1 cm. Two live *Reophax* spp. were also found and these make up 14% of the live assemblage. Live species present in low abundances include *Discammina compressa*, *Haplophragmoides sphaeriloculus*, *Reophax pilulifera*, *Psammosiphonella discreta*, *Saccammina sphaerica*, *Bolivina albatrossi*, *Bulimina striata*, *Discorbina* sp. A and *Uvigerina mediterranea*. Collectively,



**TEXT-FIGURE 9**  
 Comparison of successions recovered at JCR123-11V and JC19-32M. The position of the serpulid encrusted limestone hardground is indicated in both cores. The presence of the three ash layers from 1997, 2003 and 2006 are only seen in JC18-32M. The 'c' ornament indicates high carbonate content while the dark shading records increase levels of ash.

TABLE 1  
Data on the distribution and numbers of foraminifera in cores JC18-21M and JC18-25M.

Sample	Depth in core	Number of individuals			Total number of species	Fisher $\alpha$ diversity
		Live	Dead	Total		
JC18-21M >150 $\mu$ m	0-1 cm	32	275	308	65	25.16
	1-2 cm	10	294	304	78	33.93
	2-3 cm	0	306	306	72	29.68
	3-4 cm	3	309	312	82	36.23
	4-5 cm	0	319	319	79	33.60
	5-6 cm	0	301	301	82	37.11
	6-7 cm	0	300	300	74	31.40
	7-8 cm	0	303	303	66	26.00
	8-9 cm	0	313	313	74	30.59
	9-10 cm	0	301	301	70	28.65
JC18-25M >150 $\mu$ m	0-1 cm	35	100	135	23	7.96
	1-2 cm	0	24	24	6	2.56
	2-3 cm	6	50	56	18	9.18
	3-4 cm	23	151	174	43	18.26
	4-5 cm	40	209	249	48	17.69
	5-6 cm	12	170	182	39	15.22
	6-7 cm	4	62	66	30	21.22
	7-8 cm	6	179	185	63	33.67
	8-9 cm	8	295	303	77	33.29
	9-10 cm	4	305	309	78	33.58
	10-11 cm	3	299	302	86	40.12

these species make up the remaining 37% of the live assemblage.

The dead assemblage of the surface layer is also composed of epifaunal and infaunal detritivores. The dominant species include *B. aculeata*, *V. jeffreysii*, *T. inflata*, *B. albatrossi* and *Reophax* spp. These species make up 63% of the dead assemblage.

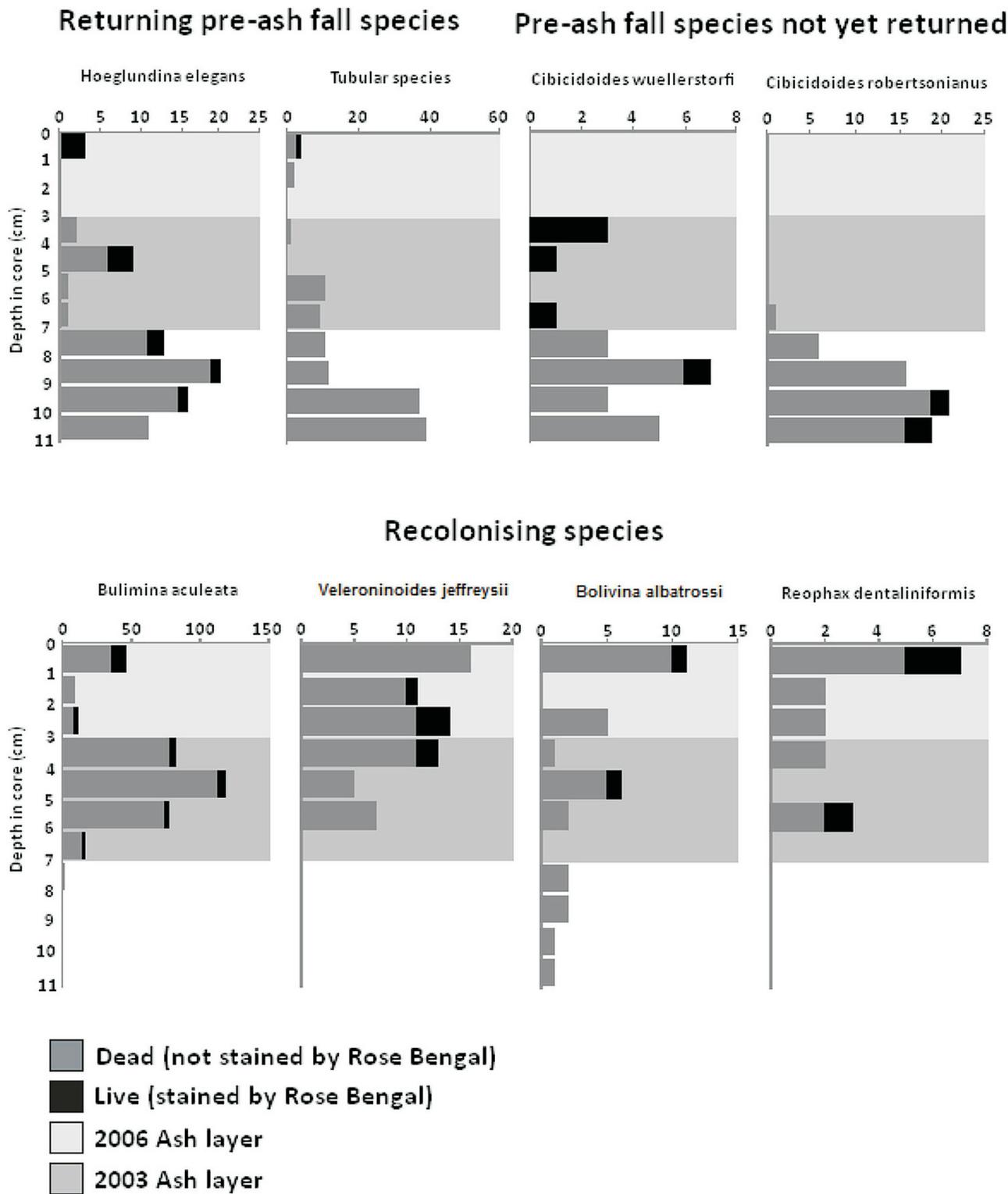
For the total assemblage, the diversity of the surface sediment is very low, with a Fisher  $\alpha$  index of 8 (text-figs 8, 10; Table 1). This is extremely low when compared to the near-surface natural assemblage at site JC18-21 which has a value of 25.2. The abundance of benthic foraminifera in the surface sediments is high: there are 88 benthic foraminifera per gram (BF/g) in the surface 1 cm. These values are to be expected as re-colonizing assemblages are often characterized by low diversity but high abundance.

Throughout core JC18-25M the diversity fluctuates, coinciding with variations in ash content. Between 1 and 3 cm, within the more recent volcanic deposit, the abundance of benthic foraminifera is very low, with an average of 12 BF/g. The diversity is also low, with an average Fisher  $\alpha$  diversity of 6. At the top of the earlier volcanic deposit, between 3 and 5 cm, the abundance (average 69 BF/g) and diversity (average  $\alpha$  18) increases. This represents the former ash fall community that would have been recolonizing the earlier ash deposit before the arrival of the 2006 volcanic ash. Through the coarser volcanic sediment found between 5 and 7 cm, the abundance (average 24 BF/g) decreases, but the diversity increases slightly to an average Fisher  $\alpha$  of 24. Towards the base of the core from 7–11 cm, the hemipelagic sediment contains benthic foraminifera of high abundance and diversity. This represents the pre-ash fall assemblage and is comparable to the natural assemblage of site JC18-21. The average Fisher  $\alpha$  diversity of this section is 35 (natural assemblage 31.2). Between 7 and 8 cm, the boundary layer, as described previously, has caused a relatively low abundance of 48 BF/g. However, between 8 and 11 cm, the average abundance is extremely high with 669 BF/g which is comparable to the abundance of the natural assemblage (655 BF/g).

The abundance of many of the species present in JC18-25M fluctuates throughout the core. The assemblage includes *H. elegans*, *Cibicidoides* spp., *B. aculeata*, *V. jeffreysii*, *B. albatrossi*, *Reophax* spp. and tubular species (text-fig. 10; Plate 1). At the top of the earlier volcanic deposit, between 3 and 5 cm, the assemblage is similar to that at the top of the most recent volcanic deposit. The most dominant species are infaunal and epifaunal detritivores and include *B. aculeata*, *V. jeffreysii*, *Cibicides* spp. and *H. elegans*. *B. aculeata* alone comprises 47% of the total assemblage, but collectively, these species make up 63%. There are also several stained specimens found in this section of the core which will be discussed later. It is evident that some species absent in the pre-ash fall assemblage now appear in, and above, the volcanic deposits (between 0 and 7 cm). These include *Nodulina dentaliniformis*, *B. aculeata* and *V. jeffreysii*. Other species that appear to have been struggling in the pre-ash fall environment seem to be thriving in the ash layers, shown by an increase in abundance. For example, *B. albatrossi* (text-fig. 10) increased from 5 specimens in 10 g of sediment at 7 to 8 cm, to 21 specimens in 10g of sediment at 4 to 5 cm. Text-figure 10 also shows that some species that were present in the pre-ash fall assemblage in large numbers were able to re-colonize the earlier volcanic deposit but after further disturbance by the 2006 deposit, have only just begun to return. Small numbers of *H. elegans* and several tubular species were found in the surface sediments of JC18-25M, some of which were found to be live (text-fig. 10). Other pre-ash fall species, such as *C. wuellerstorfi* and *C. robertsonianus* had not yet returned to the area at the time of most recent sampling.

The pre-ash fall assemblage, situated between 7 and 11 cm, is mainly composed of tubular and epifaunal species. *S. ramosa*, *R. abyssorum*, *Cibicidoides pachyderma*, *H. elegans* and *Pullenia quinqueloba* make up 21% of the total assemblage. However, the most abundant species are typical r-strategists; *R. spiculifer* and *R. scorpiurus*. *Reophax* spp. alone make up 12% of the total assemblage. Some stained benthic foraminifera were also found in this interval, although, it is unlikely that the protoplasm stained was actually alive at the time of collection.

Live benthic foraminifera were found in varying numbers throughout core JC18-25M (text-fig. 10). Most forms are represented to differing depths; however, the dominant species are *B. aculeata*, *Reophax* spp., *Cibicides* spp. and *Cibicidoides* spp.. In general, the peaks and troughs of the live assemblages are replicated by the total assemblages (live and dead) of these species throughout the core, but with fewer numbers. There is an obvious peak in live (stained) foraminifera between 3 and 6 cm for all the dominant species except *Reophax* spp., which appear to die out completely. This shows that re-colonization of the 2003 volcanic deposit took place, before being decimated by the 2006 deposit. The fluctuations of these species also demonstrate patterns in recolonization. Text-figure 10 shows that as the number of *Reophax* spp. (r-strategists) decreases, the numbers of the other species; *B. aculeata*, *Cibicides* spp. and *Cibicidoides* spp., (secondary recolonizers and k-strategists) increases. This is because until the numbers of the opportunistic *Reophax* spp. decrease (usually due to limiting resources) there is not enough ecological space for other species to thrive. At 3–4 cm, the number of secondary re-colonizers and K-strategists decreases. This is probably due to disturbance, most likely ash fall. Various volcanic events occurred throughout 2004 and 2005 (MVO, 2008) and may have deposited some fine ash in this area, creating enough disturbance to reduce the numbers of k-strategists. Cor-



TEXT-FIGURE 10

Distribution of foraminifera in JC18-25M showing live and dead numbers within the ash layers from 2003 and 2006. The stained assemblage in the upper layers of the 2003 ash is probably due to the fact that this assemblage was alive when the 2006 ash was deposited and the protoplasm preserved in the oxygen-free sediment below the 2006 ash (Fones, *pers. comm.* 2008; Jones and Gislason 2008).

respondingly, the numbers of *Reophax* spp. between 3 and 4 cm increases, possibly in reaction to this disturbance.

This trend also appears to apply to the hemipelagic sediments below 7 cm. Here, there are no *B. aculeata* and higher numbers of stained *Reophax* spp. compared to *Cibicidoides* spp. and *Cibicides* spp. Similar to the increase in *Reophax* spp. seen between 3 and 4 cm, this may signify the introduction of fine ash from small volcanic events that lead up to the explosive event of July 2003.

The natural assemblage (site JC18-21) is dominated by agglutinated tubular and branching forms (Plate 1), which make up 33% of the total assemblage in the top 2 cm of the core. Other dominant forms include agglutinated elongate uni- and multi-serial taxa, such as *Reophax* spp., broad planispiral and low trochospiral, such as *Cyclammina* spp., hyaline concavo-convex low trochospiral, such as *Cibicidoides* spp. and biconvex trochospiral, such as *Hoeglundina* spp. These 4 forms combined make up 43% of the total assemblage of the surface 1 cm. The dominant microhabitat for these forms is epifaunal, although agglutinated elongate species are generally considered infaunal.

The ash fall assemblage (site JC18-25, 0–1 cm) is dominated by hyaline tapered rounded elongate tri-, bi- and uniserial forms (N), such as *Bulimina* spp. This group make up 38% of the total assemblage of the surface 1 cm of the core. Other dominant forms include agglutinated elongate uni- and multiserial forms, such as *Reophax* spp., planispiral, streptospiral sub-sphaerical/flattened, such as *Glomospira* spp. and broad planispiral, low trochospiral, such as *Trochammina* spp. These 3 forms combined make up 41% of the total assemblage.

The former ash fall assemblage found between 3 and 5 cm in JC18-25M is also dominated by hyaline tapered rounded elongate tri-, bi- and uniserial forms. This morphotype makes up 52% of the total assemblage. Other dominant forms include agglutinated elongate uni- and multiserial, planispiral, streptospiral sub-sphaerical/flattened, hyaline biconvex trochospiral and porcellaneous elongate to ovate quinqueloculine. These 4 forms make up 31% of the total assemblage. There are also a number of plano-convex low trochospiral species, such as *Cibicidoides* spp. and *Cibicides* spp. between 4 and 5 cm, making up 5% of the 1 cm sample. These morphotypes are spread across several microhabitats; epifaunal, infaunal and shallow infaunal.

The pre-ash fall assemblage (site JC18-25, 7–11 cm) has much more of a spread of morphotypes. The most dominant forms are agglutinated elongate uni- and multiserial, hyaline biconvex trochospiral and tapered rounded elongate, tri-, bi- and uniserial. These 3 forms make up 47% of the total assemblage. Slightly less dominant forms include agglutinated tubular and branching, broad planispiral and low trochospiral and porcellaneous elongate to ovate quinqueloculine. These make up 26% of the assemblage. This spread of morphotypes is comparable to that of the natural assemblage. Similar to the former ash fall assemblage, the dominant morphotypes of the pre-ash fall assemblage are spread across several micro-habitats; epifaunal, infaunal and shallow infaunal.

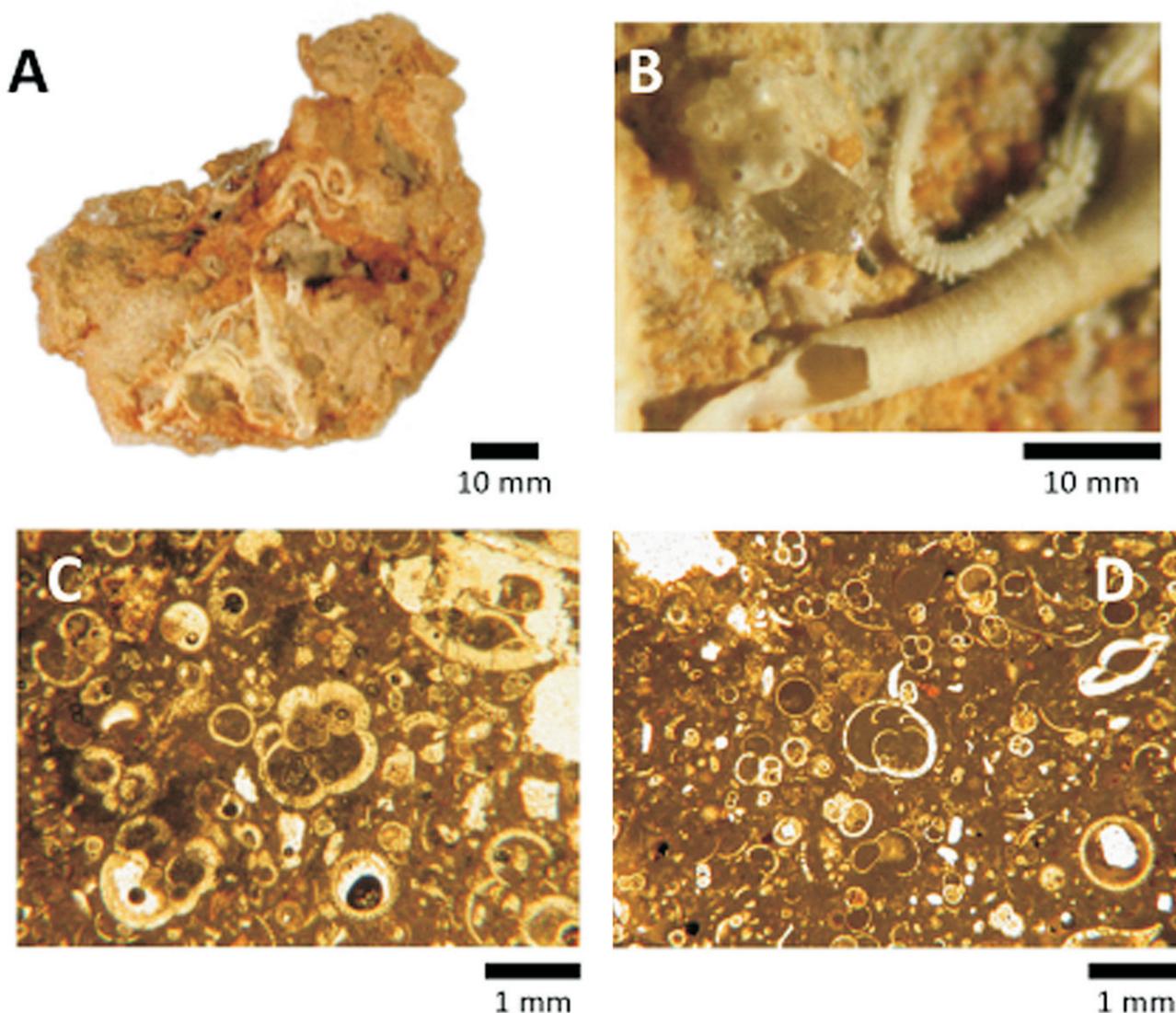
#### JC18-32M

Core JC18-32M recovered only ~16 cm of sediment (text-fig. 9) but records three separate volcanic events, each with erosive

bases and a distinctive graded profile. Below the lowermost volcanic event there is, from 8.5 cm –16 cm bsf, typical buff-colored pelagic sediments below which are the limestone ‘blocks’ that jammed in the megacorer, thereby terminating the coring process. In this core there are 8.5 cm of very soft, almost fluid, ash-rich sediment and – during extrusion – there was some expansion and collection of the 1 cm slices was challenging. As a result of these expanding clays, the individual samples will have contained sediment that may have crossed the undulating, and erosive, boundaries between the individual depositional events. Very few of the foraminifera are stained with rose Bengal and all of these are only faintly colored; this suggests that they may not have been living at the time of collection. None of the foraminifera in the surface sample (JC18-32M, 0–1 cm) were stained. The majority of the foraminifera in the samples down to 9 cm in the core were small (<150  $\mu\text{m}$ ) except for a few individuals (*Amphistegina lessonii* in JC18-32M, 7–8 cm and a fragmentary peneroplid in JC18-32M, 1–2 cm) that appear as though they are transported. The coral fragments in JC18-32M, 8–9 cm are clearly displaced although the same sample contained large examples of *Saccorhiza ramosa*, *Rhizammina algaeformis* and *Clavulina* spp. which probably originated from the uppermost carbonate-rich sediment accidentally included in the sample during collection (rather than being transported in the base of the overlying volcanoclastic sediments. Sample JC18-32M, 7–8 cm also contained a mixed assemblage including *A. lessonii*, *R. algaeformis*, a fragmentary *Reophax scoriurus* and a large *Pyro fornasini*. The assemblage of small (<150  $\mu\text{m}$ ), benthic foraminifera are reminiscent of the transported specimens described by Murray (1965) and Hart et al. (2017) after storms in the English Channel and it is possible that many of these individuals have been picked up by the turbidity currents transporting the ash-rich sediments (see Trofimovs et al. 2009).

All the samples from the volcanoclastic part of the core contained small *Bulimina* (mainly *Bulimina aculeata*), *Cibicidoides mundulus*, *Cibicidoides* spp., *Cyclogyra* spp., fragmentary *Dentalina* spp., *Globocassidulina* spp., *Fursenkoina* spp., *Hansenisca soldani*, *Hoeglundina elegans*, *Lagena* spp., *Planulina ariminensis*, *Quinqueloculina* spp., *Spiroloculina* spp., *Stainforthia* spp. and *Uvigerina* spp.; a typical Caribbean Sea assemblage (Culver and Buzas 1982).

JC18-32M was collected in December 2007 and the uppermost ash event might, therefore, have been the May 2006 eruption. The lack of a distinct assemblage of living foraminifera in the surface sample (0–1 cm) indicates that 18–19 months after the eruption, sea-floor recolonization was probably just beginning to occur. The middle ash event may have been the July 2003 eruption and the lowermost ash related to the June 1997 eruption that destroyed the town of Plymouth on Montserrat. In the centre of the Bouillante-Montserrat Graben several of the JCR123 cores (Trofimovs et al. 2006, text-fig. 3; Trofimovs et al. 2009, text-fig. 3) show ‘Unit 1, a volcanoclastic turbidite sequence from the 1995–2003 eruptions’. Core JC18-32M clearly includes these events, with the finer sediment from the turbidite flows settling out on the flanks of the Kahouanne volcanoes. Trofimovs et al. (2006, text-fig. 4) show the presence of ‘bioclasts’ (as reported above) but indicate the presence of several significant eruption events; several more than JC18-32M. As site JC18-32M was east of the graben, and at a higher elevation, it is unsurprising that fewer events were recorded.



TEXT-FIGURE 11

Appearance of the serpulid-encrusted hardground in Core JCR123-11V. **A.** Appearance of one of the limestone blocks that jammed into the megacore. **B.** General view of two of the serpulid tubes. **C.** This-section micrograph of the limestone with a specimen of *G. menardii* in the centre of the field-of-view. **D.** Thin-section micrograph of the limestone with a range of both large and small planktic foraminifera visible. The field-of-view of the thin-sections (**C** and **D**) is 6 mm.

As JCR123-11V, in one of the former craters of the Kahouanne volcanoes, recorded no ash-fall deposits at the top of the core, it is assumed that JC18-32M received the volcanic sediments by way of pyroclastic flows down the Tar Valley and that the ash-rich sediments were delivered by the distal parts of turbidity currents. The time scale for the delivery of these ash-rich sediments are probably the 1997/1998 large eruptions (which destroyed Plymouth), the June 2003 eruption and the May 2006 eruption; the core being collected in December 2007. All these eruptions are recorded on the Montserrat Volcano Observatory website ([www.mvo.ms](http://www.mvo.ms))

#### JCR123-11V

JCR123-11V was located in one of the former ‘craters’ of the Kahouanne volcanoes to the south-east of Montserrat. This

vibrocore recovered a thickness of hemipelagic sediments which grade downwards into black, basaltic ash. The transition from the ash to the overlying hemipelagic sediments, therefore, provides a record of the possible onset of normal, carbonate-rich sedimentation following the end of volcanism at the site. Above this transition there is no evidence of volcanic sediment and the area appears to have escaped any further impact by volcanic ash, despite the presence of volcanic sediments in the nearby Bouillante-Montserrat Graben. The beige-colored, serpulid-encrusted limestone (described below) occurs within the carbonate succession (text-fig. 9).

The samples from the carbonate-rich succession include all the expected planktic foraminifera (*Globigerinoides conglobatus* (Brady 1879), *G. ruber* (d’Orbigny 1839), *G. sacculifer* (Brady 1877), *Globorotalia menardii* (d’Orbigny 1865), *Neoglobo-*

TABLE 2  
Data on the distribution and numbers of foraminifera in core JCR123-11V.

Depth below the sea floor (cm)	2	5	8	20	23	26	29	32	35	38	41	44	47	65	85	105	125	145	165	s.a.	
Agglutinated tubes	1	2	1			2							1								7
<i>Amphicoryna</i> sp.		1																			1
<i>Amphistegina</i> spp.	1			1						1											3
<i>Cibicoides mundulus</i>		1					3	1	1	1	1	2	1	5	2	2	1	6	5		32
<i>Cibicoides</i> spp.		1								1											2
<i>Cornuspira</i> sp.						2			1			1									4
<i>Cymbaloporetta</i> sp.										1			1								2
<i>Dentalina</i> spp.		1		1	1	1			1		1						1				7
<i>Euloxostoma</i> sp.																		1			1
<i>Globocassidulina subglobosa</i>					1									7	7	8	1	1			25
<i>Globocassidulina</i> sp.				1																	1
<i>Gyrogonoides</i> spp.	2				1			1	5	4			1								14
<i>Hoeglundina elegans</i>	1		1		1	1			1			4		6	3	2	1				21
<i>Hyalinea</i> sp.					1						1				1						3
<i>Lenticarina</i> sp.						1													1		2
<i>Lenticulina</i> spp.	1	1									1	1	3	1		1					9
<i>Loxostomum</i> sp.															1						1
<i>Multifidelia</i> sp.		1	1	1	1			1	1	1		1									9
<i>Osangularia</i> sp.					1			3			3		3				1	1	2		14
<i>Planulina ariminensis</i>		1	2									2			1			3	1		10
<i>Planulina</i> sp.									1												1
<i>Pyrgo fornasinii</i>				1			1	1		1	1		1	2	2	1		2			13
<i>Pyrgo</i> spp.												1			1						2
<i>Quinqueloculina</i> spp.					1							1	2		1					1	6
<i>Rosalina</i> spp.	1								1												2
<i>Siphonina</i> sp.		1	1	1							1						2				6
<i>Stylostomella</i> sp.									1												1
<i>Trifarina</i> sp.						1											1				2
<i>Uvigerina</i> spp.		1			1		1		4		1				1						9
Totals	7	11	6	5	9	9	5	7	13	9	9	14	11	23	18	15	8	16	10		

*quadrina dutertrei* (d'Orbigny 1839) and *Globorotalia truncatulinoides* (d'Orbigny 1839)) as well as a diverse pteropod/heteropod assemblage (Messenger et al. 2010). At a depth of ~50 cm in the core (text-fig. 9) the ash content of samples increases and at a depth of ~65 cm there is a distinct color change to a dark gray or black ash with only rare, cream-colored particles (mainly foraminifera). This implies that this ash is almost certainly reworked, especially between 65–50 cm. In the core above 50 cm there is almost no indication of even fine-grained ash and the volcanic events recorded in JC18-32M are not present. It would, therefore, seem likely that the three events recorded in JC18-32M were not direct ash-fall events but the distal parts of turbidity currents emanating from the Tar Valley Fan and flowing onto the flanks of the former volcanic centres.

The most distinctive feature of JCR123-11V is the presence of buff-colored limestone 'blocks' that are encrusted by a significant variety of calcareous worm tubes (serpulids). In thin section (text-fig. 11) these limestones are rich in planktic foraminifera and holoplanktonic gastropods; an assemblage identical to the enclosing sediments. Some of the limestone 'blocks' appear to be bored, possibly suggestive of a hardground. Sedimentation rates in the area would indicate that the limestones are enclosed by sediments of ca. 10,000–11,000 ys BP. The percentages of *G. menardii* in the core indicate that, above ~60 cm, the sediments fall in Zone Z of the Holocene (Ericson and Wollin 1956, 1968; Reid et al. 1996; Rau et al. 2002)

Benthic foraminifera are also present (Table 2) but many of the taxa may be reworked within the mixed ash/carbonate part of the core. The species present at a depth of 165 cm bsf

(*Cibicoides mundulus*, *Osangularia* spp., *Quinqueloculina* spp. and *Planulina ariminensis*) may, therefore, be the result of transportation rather than direct sea floor recolonization.

*Cibicoides mundulus*(50%)

*Osangularia* spp. (20%)

*Quinqueloculina* spp.(20%)

*Planulina ariminensis*(10%)

At a depth of 145 cm bsf, the assemblage is similar, including:

*Cibicoides mundulus*(37.50%)

*Planulina ariminensis*(18.75%)

*Pyrgo fornasinii*(12.50%)

The distribution of the various taxa (Table 2) shows no discernable pattern and, as the benthic assemblage is often limited to only a few individuals per sample; this is often typical of a normal pelagic environment. It may also be the result of the transportation noted above. Fragments of tubular agglutinated foraminifera are rare, with only a slight increase above 26 cm bsf. *Reophax* sp. is not recorded in JCR123-11V. The location of the drill site, within an extinct volcanic centre, at a significant elevation above the surrounding sea floor probably limited re-colonization to the dispersal of propagules (Alve, 1999; Alve and Goldstein, 2002, 2003, 2010, 2014; Goldstein and Alve, 2011) and not direct migration. The taxa recorded in core JCR123-11V are, therefore, more comparable to the morphotypes recorded by Finger and Lipps (1981) and Gray et al. (2003).

### Preservation of the benthic foraminifera

SEM images of several rose Bengal stained specimens of *B. aculeata* and *C. wuellerstorfi* were produced to investigate the condition of stained individuals found beneath the 2006 volcanic deposit. By comparing these foraminifera to ones which were undoubtedly alive upon collection at the surface of the core, it can be determined whether the stained foraminifera found below the 2006 ash were alive at the time of collection.

The pores and surface structures of stained *B. aculeata* found beneath the 2006 ash (3–4 cm) in core JC18-25M are comparable in condition to those found at the surface of the same core (0–1 cm). The pores do not appear to be blocked by debris and the surface structure is not etched or damaged. However, stained *B. aculeata* from the surface of the core have an inner membrane not found in specimens collected from beneath the ash. Furthermore, the protoplasm of specimens of *B. aculeata* and of *C. wuellerstorfi* collected from below the 2006 ash contain obvious pieces of foreign debris and parts of the wall structures of both species show signs that they are breaking down from the inside out.

### Changes in benthic foraminiferal assemblages

The natural assemblage of benthic foraminifera found in core JC18-21M is comparable to other undisturbed deep-sea foraminiferal communities (Hess and Kuhnt 1996; Havach and Collins 1997) and to typical benthic foraminiferal assemblages found in the Caribbean (Culver and Buzas 1982). At site JC18-21, the high diversity and abundance of benthic foraminifera, in addition to the presence of K-strategist species, such as *Cibicidoides* spp., *H. elegans* and tubular forms, indicates that this is a low stress environment. It is, therefore, representative of a natural assemblage and is a good comparison to the pre-ash fall assemblage of site JC18-25.

The pre-ash fall and the natural community have comparable abundances (BF/g) and diversity (Fisher  $\alpha$ ) and contain a similar assemblage. This includes a number of epifaunal and tubular K-strategist species as described above. They also contain similar morphogroups representative of low stress environments.

During the May 2006 eruption of the Soufrière Hills volcano, site JC18-25 was completely smothered by 3 cm of ash, decimating the benthic foraminiferal community. It is apparent however, that only 19 months after this complete decimation (from May 2006 to December 2007) the re-population of this site is relatively advanced. The ash fall surface assemblage, which is present in the first 1 cm of the sediment, is composed of a low diversity, highly abundant variety of species with a range of morphotypes.

The earlier colonizers (r-strategists) are represented within the dead assemblage. West of Mt Pinatubo, Hess and Kuhnt (1996) considered the earliest colonizers to be small species of *Textularia* followed by *Reophax* and *Quinqueloculina* spp. However, in this study, the early colonizers appear to be slightly different; there are no *Textularia* spp. or *Quinqueloculina* spp. present in the surface layer. Instead, *B. aculeata*, *V. jeffreysii*, *T. inflata*, *B. albatrossi* and *Reophax* spp. are present. *Reophax* spp. are typical r-strategists and were likely the first colonizers of this area following the ash-fall event. They would have taken advantage of the lack of predation and competition presented directly after the ash deposit arrived. Other species dominant in

TABLE 3

Recovery from volcanic activity; a comparison of the recovery pattern from off-shore Mt Pinatubo and in Port Foster (Deception Island, Southern Ocean).

<p><b>Relatively thin ash-fall layers on the ocean floor:-</b></p> <ul style="list-style-type: none"> <li>- months or a few years to recover</li> <li>- often led by species of <i>Reophax</i>, <i>Bulimina</i></li> </ul> <p><b>The Pinatubo Model</b></p>	<p><b>Major eruptions and extinct or dormant volcanic centres:-</b></p> <ul style="list-style-type: none"> <li>- lengthy process</li> <li>- involves many taxa</li> <li>- <u>not</u> led by species of <i>Reophax</i>, <i>Bulimina</i></li> </ul> <p><b>The Deception Island Model</b></p>
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the dead assemblage are not typical r-strategists, but most likely transitional species that would have lived alongside the r-strategists and gradually replaced them as the environmental conditions improved. These include *T. inflata* and *V. jeffreysii*. After the eruption of Mt Pinatubo, Hess and Kuhnt (1996) found that a second succession included individuals of *Trochammina* spp. This may indicate that they are, along with *V. jeffreysii*, later inhabitants. *Bulimina aculeata* and *B. albatrossi* are common inhabitants of stressed, oxygen-depleted environments (Bernhard and Sen Gupta 2002). *B. aculeata* is not present and *B. albatrossi* is only present in low numbers in the pre-ash fall community. Both species however, appear to be thriving within and above the ash layers. The species described above are present in the dead assemblage in high numbers owing to their capability of rapid dispersion. This shows that a very high proportion of the total assemblage is made up of r-strategists, creating a low diversity and signifying the first stages of recolonization of the ash deposit.

The live assemblage of the surface layer of site JC18-25 is composed of species more representative of low stress environments (K-strategists). These include *Hansenisca soldanii*, *Hoeglundina elegans* and several tubular species. The number of live specimens in this layer is low, although this may be due to the high proportion of dead tests created by the early population boom of r-strategists. Several of the dominant live species found here are also present in the natural community of site JC18-21 and this shows that the area is returning to its natural assemblage. The most dominant live species is *B. aculeata*. As discussed previously, this species is a common inhabitant of stressed oxygen-depleted environments and may indicate that whilst the area is recovering, the environment is still very hostile. It was also noted that several polychaete worms were present to a depth of 3 cm and bivalve molluscs to a depth of 2 cm in the sediments of core JC18-25M. This signifies the presence of burrowing fauna and predators, showing a fairly advanced stage of re-colonization. This stage of re-colonization is far more advanced than the stage reached 3 years after the eruption of Mount Pinatubo (Hess and Kuhnt 1996). Hess *et al.* (2001) observed that 5 years after the Mt Pinatubo eruption, the assemblage was further advanced, containing species of *Cibicidoides wuellerstorfi* and tubular forms such as *Rhabdammina abyssorum*. It had, however, not reached the diversity of the pre-ash fall assemblage and was therefore not fully recovered. In this study, some of the pre-ash fall species, such as *R. abyssorum* have returned to the surface sediments of site JC18-25; however, some such as *Cibicidoides wuellerstorfi*, were yet to return in December 2007.

The composition of morphotypes present in the ash fall community also shows differences between the ash fall assemblage and the natural (and pre-ash fall) assemblage. In the natural assemblage, the dominant morphotypes are agglutinated tubular and branching; elongate uni- and multiserial; calcareous hyaline concavo-convex low trochospiral and biconvex low trochospiral. In general, these groups are typical of low stressed environments, living in epifaunal or shallow infaunal microhabitats. The dominant morphotypes of the ash fall assemblage include agglutinated elongate, uni- and multiserial; planispiral, streptospiral subspherical or flattened; broad planispiral and low trochospiral and calcareous hyaline tapered rounded elongate, tri-, bi- and uni-serial forms. The majority of these forms are agglutinated and all live infaunally. In general, these dominant forms indicate a stressed environment. A large proportion of the ash fall assemblage, however, is made up of dead foraminifera that were alive during the first stages of recolonization and may not accurately portray the current ash fall assemblage. The dominant morphotypes therefore reflect the dead assemblage and do not correctly represent the current/live ash fall assemblage. The proportions of morphotypes of the live assemblage of the ash fall community are much more spread out. The dominant forms include morphotypes similar to the total assemblage, but also include calcareous hyaline plano-convex low trochospiral and biconvex trochospiral forms such as *Cibicidoides* spp. and *H. elegans*. These latter morphotypes live epifaunally and indicate a low stressed environment similar to the natural and pre-ash fall communities.

The peak in remains of benthic foraminifera between 3 and 6 cm in JC18-25M shows that the 2003 ash was in the process of being re-colonized when it was decimated by the 2006 ash layer. The re-colonizing assemblage of the July 2003 ash layer contained several K-strategist species, such as tubular forms and species such as *C. wuellerstorfi*, which are not yet found in the new (2006) ash fall assemblage. This reveals that it took less than 3 years (July 2003–May 2006) for site JC18-25 to return to a comparable level of development that took areas around Mt Pinatubo 5 years to reach. In addition to the presence of more K-strategist foraminifera, at 4–5 cm core depth, a tube worm similar to others found in the sediments of site JC18-21 was found. This indicates that the 2003 ash fall community was not only regaining its pre-ash fall foraminifera, but also its pre-ash fall macrofauna.

#### **Depth of stained foraminifera**

Stained benthic foraminifera were found in varying numbers throughout core JC18-25M, with a peak in numbers from 3 to 6 cm coinciding with the finer grained part of the 2003 volcanic deposit and ending at the base of the 2006 ash layer.

The sediments below the 2006 ash deposit are evidently a very hostile environment. When an ash deposit is laid down on the sea floor, it smothers the sediments below, preventing the penetration of oxygen and causing anoxic conditions. The oxygen profile of core JC18-25M shows that this has occurred at site 25 where there is a rapid decrease of oxygen in just 2 cm of sediment (Fones, *pers. comm.*, 2008; Jones and Gislason, 2008; Henbury et al. 2012). Such a distribution of live benthic foraminifera at depth is not, therefore, anticipated although several scenarios could lead to this unlikely habitation below the 2006 ash layer.

It is possible that during sampling the core was contaminated by smearing of the sediments as the corer was pushed in. This is always a possibility and is difficult to eliminate, however, precautions were taken where possible to minimize the effects. When the core was sliced into 1 cm samples onboard the research vessel, the outer layer of the sample was removed. Core JC18-21M shows no sign of this contamination and it is therefore unlikely that the trend found between 3 and 6 cm in core JC18-25M could be caused in this way. The correlation between several stained individuals of different species present in the layer also shows that this is not an isolated occurrence of just one or two individuals. Similar patterns have been observed by other authors. Hess and Kuhnt (1996) found that the thicker parts of the Mt Pinatubo ash was lethal for most of the benthic foraminifera, however, some stained epifaunal suspension feeders were found below the layer of ash. This was attributed to the ability of deep-sea foraminifera to withstand long periods of starvation by metabolising their own protoplasm (Gooday 1994). It was also suggested that the ash layer may have favoured their survival by removing the threat of predators and increasing the availability of food (Hess and Kuhnt 1996). Hess and Kuhnt (*op. cit.*) also noted that dead agglutinated forms were unusually well preserved below the ash layer.

It is well known that several benthic foraminifera can migrate vertically through sediments in response to environmental conditions. Some benthic foraminifera are able to move with considerable speed, approaching around  $100 \mu\text{m min}^{-1}$  (Kitazato 1988; Alve and Bernhard 1995). *B. aculeata* is by far the dominant stained species found between 3 and 6 cm in core JC18-25M. It is however, generally regarded as a shallow infaunal species (Mackensen et al. 2000) that is often found exclusively in or on the top 2 cm of sediment (Mackensen and Douglas 1989). Several authors have previously found *B. aculeata* living deeper in sediments. In the South Atlantic, Mackensen et al. (2000) found a strong dominance in the uppermost centimetre of sediment with a rapid decrease to a low but constant standing stock in the deeper sediment up to 11 cm. Off Japan, Ohga and Kitazato (1997) recorded high numbers of *B. aculeata* down to 15 cm depth. Mackensen et al. (2000) attributes their presence at depth to an ability of rapid vertical migration in order to follow optimum microenvironmental conditions in terms of food availability and oxygen content of interstitial waters.

It is also generally appreciated that bolivinids such as *B. aculeata* are tolerant of low oxygen conditions (Gooday 1994; Smart 2002). Alve and Bernhard (1995) found a species of *Bulimina* to be very tolerant of low oxygen conditions but migrated, along with all other surviving species, out of the sediment and onto polychaete tubes at extremely low concentrations. It is therefore likely that although *Bulimina aculeata* is able to migrate through the sediment, it would be unable to withstand such low oxygen concentrations. Several stained *Reophax* individuals were found at 3–4 cm in JC18-25M. Hess and Kuhnt (1996) also found several live *Reophax* spp. up to depths of 10 cm, although, Alve and Bernhard (1995) suggest that *Reophax* spp. are unable to tolerate low oxygen conditions. Kaminski *et al.* (1995) concluded that deep water agglutinated foraminifera such as *Reophax* spp. can only survive periods of complete anoxia for around a month. It is therefore unlikely that they survived a period of 19 months beneath the 2006 ash layer. *Cibicidoides* spp. and *Cibicides* spp., which are also dominant in the stained assem-

blage from 3 to 6 cm, are generally regarded as epifaunal forms typical of low stress environments. Gooday (1994) describes them as epibenthic, living on the sediment surface or attached to substrates elevated above the sediment surface. It is therefore highly unlikely that they have migrated to depths of 11 cm or that they have been able to survive being smothered by the ash deposit.

Although several taxa have been shown to tolerate low oxygen conditions (Smart, 2002), there is no test morphology that is typically found in anoxic conditions and no species which occur exclusively under such conditions (Sen Gupta and Machain-Castillo 1993; Gooday 1994). Smart (2002) suggests that low oxygen assemblages are typically dominated by infaunal calcareous species and that some calcareous taxa have been found to be indicative of diminished oxygen. These include *Bolivina*, *Bulimina*, *Cassidulina*, *Chilostomella*, *Epistominella*, *Globobulimina*, *Furksenkoia*, *Nonionella* and *Uvigerina*. However, since these taxa also occur in well oxygenated environments, they are only indicative of depleted oxygen when their abundances are very high (Smart 2002). Several of these taxa are present within the layer of stained foraminifera at 3-6 cm, however, their abundances are not high enough to indicate a low oxygen community living in this area.

It is, therefore, most likely that the occurrence of stained and supposedly live individuals beneath the 2006 ash layer is due to the preservation qualities of the ash layer. The lack of oxygen penetrating the sediment prevents organic material from being broken down, preserving all organisms including foraminifera and their protoplasm. Therefore, when the sediment is treated with rose Bengal, these preserved soft tissues will become stained and the foraminifera will be assumed as live at the time of collection.

By comparing the SEM images of rose Bengal stained specimens of *B. aculeata* and *C. wuellerstorffii* from above and below the ash 2006 layer, a decision as to whether the specimens found deep within the core were live at the time of collection can be made. Stained specimens found between the volcanic layers (3–5 cm) in core JC18-25M appear to be comparable in condition to live specimens found at the surface of the same core. The pore structures at the surface are not blocked by debris and the surface structure has not been etched or damaged. The surface specimens of *B. aculeata* contain an inner membrane which is not present in the specimens at 3 to 5 cm. Furthermore, the protoplasm of specimens found under the 2006 ash contains obvious pieces of foreign debris. Some parts of the wall structure also appear to have begun breaking down from the inside out. It therefore most likely that the rose Bengal stained specimens found deep within the core, certainly of *B. aculeata* and *C. wuellerstorffii* and possibly of other species, were in fact not live at the time of collection but have been preserved by the ash layer. The peak in stained foraminifera below the 2003 ash layer that runs from 8 cm to 11 cm in the core shows that this process has also occurred below the 2003 ash layer. This suggests that the preservation of protoplasm in this way lasts at least 3½ years (July 2003–December 2007).

#### **Recovery of foraminifera above pyroclastic flows**

Cores JC18-32M and JCR123-11V record quite a different response to that recorded in JC18-25M. The latter site records the presence of two ash-fall events, while JC18-32M indicates the presence of three events that derive from the turbidity currents

within the Bouillante-Montserrat Graben. As a result of the uncertainty of dating each of these events, the time for recovery is even less certain. The samples from JC18-32M also contain exotic material – both fossils and sedimentary particles – derived from shallower-water environments and the record of actual recolonization is blurred as a result.

#### **DECEPTION ISLAND: RECOLONIZATION COMPARISONS**

Deception Island, in the Southern Ocean, was the location of volcanic eruptions in 1967, 1969 and 1970 (Geyer et al. 2021). These eruptions clearly decimated the benthos (Gallardo and Castillo 1968) in the caldera (known as Port Foster). The pre-eruption assemblages of foraminifera in Port Foster had been documented by Fauré-Fremiet (1914) and Earland (1934).

A sampling program was started at Deception Island sixteen months after the 1970 eruption. Some of the unique features of the sampling area are its location in an extinct volcano caldera with access to the open ocean. Re-suspension of bed sediment load is believed to have continued for some time after the initial ash fall from the eruptions. Melt water input with a large sediment load during the austral summers would also be a source of increased turbidity in the study area and clearly have an impact on any recolonization by foraminifera (Finger and Lipps 1981).

Finger and Lipps (1981) used the ‘foraminiferal number’ to express foraminiferal abundance in their study. This is calculated as the number of tests present in 1 gram of dry sediment. Finger and Lipps, (1981) reported that in 1973 the mean foraminiferal number was 6, and that this had risen to 48 by 1976. A more recent study of Deception Island in 2000 found the mean foraminiferal number to be 43 which would seem to indicate no measurable increase in foraminiferal abundance in the intervening 30 years (Gray et al. 2003). Species diversity was also found to be similar. The time period of approximately six to seven years for complete recovery of the benthic foraminiferal community is in agreement with that found by Hess and Khunt (1996) in the South China Sea. Despite these similarities, the taxonomic composition of the benthic foraminifera communities had changed. Of particular interest was that the first appearance of *Reophax dentaliniformis* (= *Nodulina dentaliniformis*) was not mentioned by Finger and Lipps (1991) but by the 2000 sampling expedition was the fourth most abundant species of foraminifera (Gray et al. 2003). This species, therefore, first appeared well into the recovery period at Deception Island.

Following the cessation of volcanic activity, Finger (1975; 1977) and Finger and Lipps (1981) described the sediments, geochemistry and foraminiferal assemblages in 250 bottom samples collected from Port Foster and the surrounding shelf in the five, successive austral summers (1972–1976). The latitude and oceanic setting means that water temperatures are low (-2°C to +2°C) and the water is quite turbid as a result of summer season run-off from the new ash deposits on the horse-shoe shaped island into Port Foster. The pH of the interstitial waters was also recorded to be low (6.6 – 6.8).

The most common taxa in the 1970s were recorded as *Rotaliammina ochracea*, *Globocassidulina crassa* and *Nonionella bradyi*. In total, Finger (1975; 1977) and Finger and Lipps (1981) recorded the presence of 94 species in 50 genera, though many were small (= juvenile?) forms. This may have been the result of a combination of the ‘spring bloom’ and the

time of sampling, effectively limiting collection to the newly generated juveniles (as suggested by Finger and Lipps 1981, p. 120). In their assemblage list, Finger and Lipps (1981, pp. 129–130, 132, 134) record a wide range of taxa, including some agglutinated taxa (*Cribrostomoides jefferysii*, *Ammodiscus incertus discoideus*, *Miliammina arenacea* and a number of *Reophax* spp., including *Nodulina dentaliniformis*).

Gray et al. (2003) described the foraminifera of the same area using samples collected from March 1999 – November 2000: the ERUPT programme (Smith et al., 2003). They noted that the increase in foraminifera recorded in the 1972–1976 period did not continue. Gray et al. (*op. cit.*) record that while *Miliammina arenacea* and *Trochammina malovensensis* were still predominant, *Globocassidulina* spp. had increased while *Stainforthia fusiformis* and *Nonionella bradyi* were less important. Most importantly, they claim that the rise in *Nodulina dentaliniformis* and *Cassidulinoides parkerianus*, which were rare in the 1970s, shows that – unlike the Mt Pinatubo records – *N. dentaliniformis* is not always the pioneer taxon in post-disturbance re-colonization.

Gray et al. (2003, figs 2, 6) collected a series of gravity cores, only one of which penetrated >50 cm. They provide data on the assemblage of foraminifera in 1999–2000 and, in their table 4, Gray et al. (2003, p. 1746) record the changes from the data provided by Finger and Lipps (1981). This, particularly, includes the change in the numbers of *N. dentaliniformis* (to 4.5% of the benthic assemblage) compared to its relatively rare occurrence in the 1970s both in Port Foster and the outer slopes of Deception Island. Gray et al. (2003, p. 1747) indicate that, while Earland (1934) had recorded the frequent occurrence of *Reophax* spp. prior to the eruptions in the 1960s and 1970, *Reophax* spp. – and especially *N. dentaliniformis* – should not be regarded as a pioneer taxon in the immediate post-eruption period, unlike the situation in the South China Sea (Hess and Kuhnt 1996) or off Nova Scotia following storms (Kaminski, 1985). It is notable that both Hess et al. (2001) and Gray et al. (2003) suggest stabilization of the assemblage is normally 6–7 years post-eruption.

## CONCLUSIONS

Several things can be concluded from this study:

In December 2007, Site JC18-25 was at a relatively advanced stage of recolonization. The assemblage included several k-strategists and had regained several of the pre-ash fall species. It was further advanced than the stage at which Mt Pinatubo had reached after 3 years, but not as advanced as Mt Pinatubo had reached in 5 years. The assemblage of the previous re-colonized ash layer (2003) at this site was also not fully recovered 3 years after the 2003 eruption of the Soufrière Hills Volcano but was more advanced than the current stage of re-colonization of the 2006 ash layer. It was, therefore, predicted that by 2009 the stage of re-colonization reached on the 2006 ash would have been comparable to that achieved by the previous re-colonizing assemblage. The presence of several pre-ash fall species in the ash fall community and its rapid recovery suggest that 2006 ash deposit had been re-colonized by foraminifera from adjacent unaffected areas. It was also evident that the benthic foraminiferal community had not adapted its assemblage to tolerate the periodic disturbances which it has been experiencing. This may be a factor to look out for in further studies of the area, especially if the eruptive events become more frequent or significantly larger in volume.

Rose Bengal stained benthic foraminifera found at depth below both the 2006 and 2003 ash layers at site JC18-25 were not alive at the time of collection as these individuals were, probably, preserved by the lack of oxygen beneath the ash layers. It was assumed that individuals found beneath the 2003 ash layer were preserved by the 2003 ash and that the individuals between the 2003 and 2006 ash layers were preserved by the 2006 ash layer. Benthic foraminiferal protoplasm and chamber linings may, therefore, remain preserved in a detectable condition for at least 3 and a half years under ash deposits that affect oxygen levels in the intervening sediments.

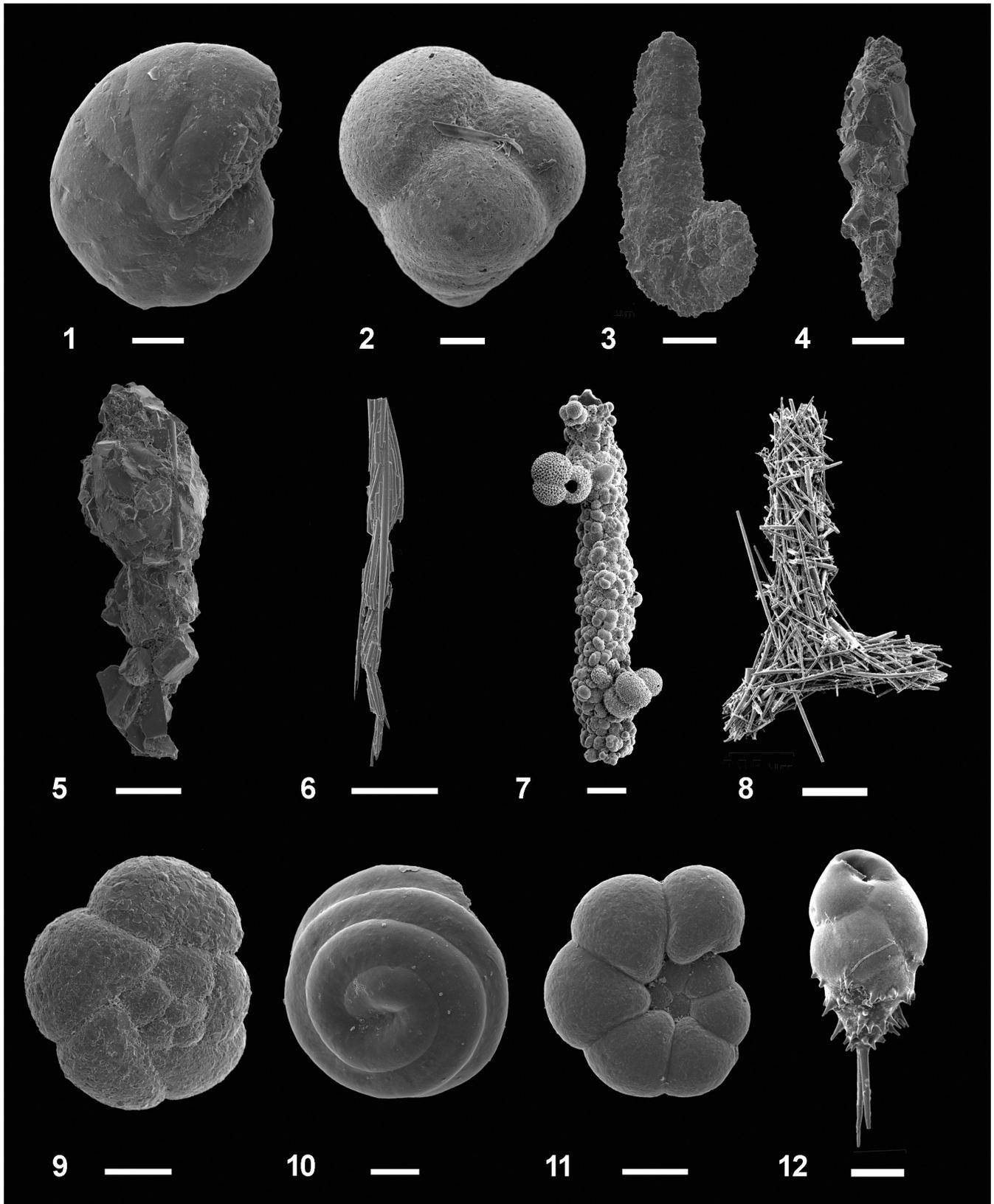
While the recovery patterns to the west and south-west of Montserrat were comparable to those recorded to the west of Mt Pinatubo, the re-colonization of the volcanic centres to the east

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## PLATE 1

Selection of the foraminifera recorded in this investigation.

- |   |   |
|---|---|
| 1 <i>Cyclammina cancellata</i> , JC18-21M, 1–2 cm;    | 7 <i>Rhizammina algaeformis</i> , JC18-21M, 1–2 cm;     |
| 2 <i>Eggerella bradyi</i> , JC18-25M, 8–9 cm;         | 8 <i>Saccorhiza ramosa</i> , JC18-21M, 0–1 cm;          |
| 3 <i>Eratidus foliaceus</i> , JC18-21M, 1–2 cm;       | 9 <i>Trochammina inflata</i> , JC18-25M, 0–1 cm;        |
| 4 <i>Nodulina dentaliniformis</i> , JC18-25M, 0–1 cm; | 10 <i>Glomospira charoides</i> , JC18-21M, 1–2 cm;      |
| 5 <i>Reophax scorpiurus</i> , JC18-25M, 8–9 cm;       | 11 <i>Veleroninoides jeffreysii</i> , JC18-25M, 3–4 cm; |
| 6 <i>Reophax spiculifera</i> , JC18-25M, 8–9 cm;      | 12 <i>Bulimina aculeata</i> , JC18-25M, 2–3 cm.         |



of Montserrat followed a pattern more closely similar to that described from Deception Island in the Southern Ocean (Table 3). This confirms the suggestions made by Gray et al. (2003), though one must be careful when making comparisons between two areas that are so different in terms of climate, water conditions and the reproductive window available to the foraminifera.

This project has opened the door to a range of further studies. It provided an initial evaluation of the benthic foraminiferal re-colonization at site JC18-25. This not only contributes to our understanding of the ecology of benthic foraminifera but creates a base from which further studies can be made as part of this ongoing ecological monitoring programme. If further eruptive material does not reach site JC18-25 for some time, further stages of re-colonization may be documented, although like all studies of the marine environment, sampling expeditions are both expensive and time-consuming for those involved in their planning and implementation.

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#### REFERENCES

- AAGAARD-SØRENSEN, S., JUNTILLA, J., and DIJKSTRA, N., 2016. Benthic foraminiferal responses to operational drill cutting discharge in the SW Barents Sea – a case study. *Geophysical Research Abstracts*, 18: EGU2016–7527, 2016.
- ALVE, E., 1995. Benthic foraminiferal distribution and recolonisation of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, 25: 169–186.
- , 1999. Colonisation of new habitats by benthic foraminifera: a review. *Earth-Science Reviews*, 46: 167–185.
- ALVE, E. and BERNHARD, J. M., 1995. Vertical migratory response of benthic foraminifera to controlled oxygen concentrations in an experimental mesocosm. *Marine Ecology Progress Series*, 166: 137–151.
- ALVE, E. and GOLDSTEIN, S. T., 2002. Resting stage in benthic foraminiferal propagules: a key feature for dispersal? Evidence from two shallow-water species. *Journal of Micropalaeontology*, 21: 95–96.
- , 2003. PROPAGULE TRANSPORT AS A KEY METHOD OF DISPERSAL IN BENTHIC FORAMINIFERA (PROTISTA). *Limnology and Oceanography*, 48: 2163–2170.
- , 2010. Dispersal, survival and delayed growth of benthic foraminiferal propagules. *Journal of Sea Research*. 63: 36–51.
- ALVE, E. and GOLDSTEIN, S. T., 2014. The propagule method as an experimental tool in foraminiferal ecology. In: KITAZATO, H., and BERNHARD, J. M. Eds., *Approach to study living foraminifera – collection, maintenance and experimentation*, Tokyo: Springer, 1–12.
- BERGAMIN, L., CAPELLO, M., CARBONE, C., MAGNO, M.C., CONSANI, S., CUTRONEO, L., FERRARO, L., PIERFRANCESCHI, G. and ROMANO, E., 2016. Ecological response of benthic foraminifera to the acid drainage from mine areas. An example from the Gromolo torrent mouth (Eastern Ligurian Sea). *Geophysical Research Abstracts*, 18: EGU2016–7879, 2016.
- BERNHARD, J. M., 1988. Postmortem vital staining in benthic foraminifera; duration and importance in population and distributional studies. *Journal of Foraminiferal Research*, 18 (2): 143–146.
- , 2000. Distinguishing live from dead foraminifera: Methods review and proper applications. *Micropaleontology*, 46 (Supplement 1): 38–46.
- BERNHARD, J. M. and SEN GUPTA, B. K., 2002. Foraminifera of oxygen-depleted environments. In: Sen Gupta, B. K., Ed., *Modern Foraminifera* Dordrecht: Kluwer Academic Publishers, 201–216.
- BURKETT, A. M., RATHBURN, A. E., PÉREZ, M. E. and MARTIN, J. B., 2018. Influences of thermal and fluid characteristics of methane and hydrothermal seeps on the stable oxygen isotopes of living benthic foraminifera. *Marine and Petroleum Geology*, 93: 344–355.
- CONSOLARO, C., RASMUSSEN, T. L., PANIERI, G., MIENERT, J., BÜNZ, S. and SZTYBOR, K., 2015. Carbon isotope ( $\delta^{13}\text{C}$ ) excursions suggest times of major methane release during the last 14 kyr in Fram Strait, the deep-water gateway to the Arctic. *Climate of the Past*, 11: 669–685.
- CULVER, S. J. and BUZAS, M. A., 1982. Distribution of recent benthic foraminifera in the Caribbean region. *Smithsonian Contributions to Marine Sciences*, 14: 1–392.
- DENOYELLE, M., JORISSEN, F. J., MARTIN, D., GALGANI, F. and MINÉ, J., 2010. Comparison of benthic foraminifera and macrofaunal indicators of the impact of oil-based drill mud disposal. *Marine Pollution Bulletin*, 60 (11): 2007–2021.
- DIAS, B. B., HART, M. B., SMART, C. W. and HALL-SPENCER, J. M., 2010. Modern seawater acidification: the response of foraminifera to high  $\text{CO}_2$  conditions in the Mediterranean Sea. *Journal of the Geological Society, London*, 167: 843–846.
- DI BELLA, L., FREZZA, V., CONTE, A. M. and CHIOCCI, F. L., 2015. Benthic foraminiferal assemblages in active volcanic area of the Azores Islands (North Atlantic Ocean). *Italian Journal of Geosciences*, 134 (1): 50–59.
- EARLAND, A., 1934. Foraminifera, Part 3. The Falklands sector of the Antarctic (excluding South Georgia). *Discovery Reports*, Cambridge, Cambridge University Press, 10: 1–208.
- ELLISON, R. L. and PECK, G. E., 1983. Foraminiferal recolonisation on the continental shelf. *Journal of Foraminiferal Research*, 13: 231–241.
- ERICSON, D. B. and WOLLIN, G., 1956. Micropaleontological and isotopic determinations of Pleistocene climates. *Micropaleontology*, 2: 257–270.
- , 1968. Pleistocene climates and chronology in deep-sea sediments. *Science*, 162: 1227–1234.
- FAURÉ-FREMIET, E., 1914. Foraminifères. Deuxième Expedition Antarctique Francaise, 1908–1910, 15pp.

- FINGER, K. L., 1975. Benthic foraminifera from Deception Island, South Shetland Islands. *Antarctic Journal US*, 10 (4): 134–135.
- , 1977. Foraminiferal species obtained by R/V *Hero* from Deception Island, 1971–1976. *Antarctic Journal US*, 12 (3): 37–39.
- FINGER, K. L. and LIPPS, J. H., 1981. Foraminiferal decimation and repopulation in an active volcanic caldera, Deception Island, Antarctica. *Micropaleontology*, 27: 111–139.
- FISHER, J. K., 1999. *The recolonisation of the South China Sea by benthic foraminifera following the 1991 Mount Pinatubo eruption*. Unpublished M.Res. Thesis, University College, London.
- FRAASS, A. J., WALL-PALMER, D., LECKIE, R. M., HATFIELD, R. G., BURNS, S. J., LE FRIANT, A., ISHIZUKA, O., ALJAHDALI, M., JUTZELER, M., MARTÍNEZ-COLÓN, M., PALMER, M. and TALLING, P. J., 2017. A revised Plio-Pleistocene age model and paleoceanography of the northeastern Caribbean Sea: IODP Site U1396 off Montserrat, Lesser Antilles. *Stratigraphy*, 13: 183–203.
- GALLARDO, V. A. and CASTILLO, J. G., 1968. Mass mortality in the benthic infauna of Port Foster resulting from eruptions in Deception Island (South Shetland Island). *Istituto Antartico Chileno, Santiago, Chile, Publication*, 16: 1–11.
- GALEOTTI, S., BELLAGAMBA, M., KAMINSKI, M. A. and MONTANARI, A., 2002. Deep-sea benthic foraminiferal recolonisation following a volcanoclastic event in the lower Campanian of the Scaglia Rossa Formation (Umbria-Marche Basin, central Italy). *Marine Micropaleontology*, 44: 57–76.
- GEYER, A., PEDRAZZI, D., ALMEDROS, J., BERROCOSO, M., LÓPEZ-MARTÍNEZ, J., MAESTRO, A., CARMONA, E., ÁLVAREZ-VALERO, A. M. and DE GIL, A., 2021. Chapter 7.1, Deception Island. In: Smellie, J. L., Panter, K. S. and Geyer, A., Eds., *Volcanism in Antarctica: 200 million years of subduction, rifting and continental break-up*. *Geological Society, London, Memoirs*, 55: 667–693.
- GOLDSTEIN, S. T. and ALVE, E., 2011. Experimental assembly of foraminiferal communities from coastal propagule banks. *Marine Ecology Progress Series*, 437: 1–11.
- GOODAY, A. J., 1984. Records of deep sea rhizopod tests inhabited by metazoans in the north-east Atlantic. *Sarsia*, 69: 45–53.
- , 1994. THE BIOLOGY OF DEEP-SEA FORAMINIFERA: A REVIEW OF SOME ADVANCES AND THEIR APPLICATIONS IN PALEOCEANOGRAPHY. *Palaos*, 9: 14–31.
- GRAY, S. C., STURZ, A., BRUNS, M. D., MARZAN, R. L., DOUGHERTY, D., LAW, H. B., BRACKETT, J. E. and MARCOU, M., 2003. Composition and distribution of sediments and benthic foraminifera in a submerged caldera after 30 years of volcanic quiescence. *Deep-Sea Research Part II*, 50: 1727–1751.
- HART, K., CAREY, S., SIGURDSSON, H., SPARKS, R. S. J. and ROBERTSON, R. E. A., 2004. Discharge of pyroclastic flows into the sea during the 1996–1998 eruptions of the Soufrière Hills volcano, Montserrat. *Bulletin of Volcanology*, 66: 599–614.
- HART, M. B., MOLINA, G. S., SMART, C. W. and WIDDICOMBE, C. E., 2017. The Western Channel Observatory: benthic foraminifera in the plankton following storms. *Geoscience in South-West England*, 14 (1): 39–45. [for 2016]
- HART, M. B., MOLINA, G. S. and SMART, C. W., 2020. Estuarine foraminifera from South West England: impact of metal pollution in a mining heritage area. *Journal of Sedimentary Environments*, 5: 1–16.
- HAVACH, S. M. and COLLINS, L. S., 1997. The distribution of recent benthic foraminifera across habitats of Bocas del Toro, Caribbean Panama. *Journal of Foraminiferal Research*, 27: 232–249.
- HAYWARD, B. W., LE COZE, F., VACHARD, D. and GROSS, O., 2021. World Foraminifera Database. Accessed at <http://www.marinespecies.org/foraminifera> on 15 May 2021. doi:10.14284/305.
- HEMBURY, D. J., PALMER, M. R., FONES, G. R., MILLS, R. A., MARSH, R. and JONES, M. T. 2012. Uptake of dissolved oxygen during marine diagenesis of fresh volcanic material. *Geochimica et Cosmochimica Acta*, 84: 353–368.
- HERD, R. A., EDMONDS, M. and BASS, V., 2005. Catastrophic lava dome failure at Soufrière Hills volcano, Montserrat 12–13 July 2003. *Journal of Volcanology and Geothermal Research*, 148 (3–4): 234–252.
- HESS, S. and KUHN, W., 1996. Deep-sea benthic foraminiferal recolonization of the 1991 Mt. Pinatubo ash layer in the South China Sea. *Marine Micropaleontology*, 28: 171–197.
- HESS, S., ALVE, E., TRANNUM, H. C. and NORLING, K., 2013. Benthic foraminiferal responses to water-based drill cuttings and natural sediment burial: Results from a mesocosm experiment. *Marine Micropaleontology*, 101: 1–9.
- HESS, S., JORISSEN, F. J., VENET, V. and ABU-ZIED, R., 2005. Benthic foraminiferal recovery after recent turbidite deposition in Cap Breton Canyon, Bay of Biscay. *Journal of Foraminiferal Research*, 35: 114–129.
- HESS, S., KUHN, W., HILL, S., KAMINSKI, M. A., HOLBOURN, A. and DE LEON, M., 2001. Monitoring the recolonization of the Mt Pinatubo 1991 ash layer by benthic foraminifera. *Marine Micropaleontology*, 43: 119–142.
- JONES, R. W., 1994. *The Challenger Foraminifera*. Oxford University Press, Oxford.
- JONES, M. T. and GISLASON, S. R., 2008. Rapid releases of metal salts and nutrients following the deposition of volcanic ash in to aqueous environments. *Geochimica et Cosmochimica Acta*, 72: 3661–3680.
- JORISSEN, F. J., BICCHI, E., DUCHEMIN, G., DURRIEU, J., GALGANI, F., CAZES, L., GAULTIER, M. and CAMPS, R., 2009. Impact of oil-based drill mud disposal on benthic foraminiferal assemblages on the continental margin off Angola. *Deep Sea Research Part II: Topical Studies in Oceanography*, 56 (23): 2270–2291.
- KAMINSKI, M. A., 1985. Evidence for control of abyssal agglutinated foraminiferal community structure by substrate disturbance: results from the HEBBLE area. *Marine Geology*, 66: 113–131.
- KAMINSKI, M. A., BOERSMA, A., TYSZKA, J. and HOLBOURN, A. E. L., 1995. Response of deep-water agglutinated foraminifera to dysoxic conditions in the California Borderlands basins. In: Kaminski, M. A., Geroch, S. and Gasinski, M. A., Eds., *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera, Kraków, Poland, September 12–19, 1993*, Grzybowski Foundation Special Publication, 3: 131–140.
- KUHN, W., HESS, S., HOLBOURN, A., PAULSEN, H. and SALOMON, B., 2005. The impact of the 1991 Mt Pinatubo eruption on deep-sea foraminiferal communities: A model for the Cretaceous-Tertiary (K/T) boundary? *Palaogeography, Palaeoclimatology, Palaeoecology*, 224: 83–107.
- KITAZATO, H., 1988. Locomotion of some benthic foraminifera in and on sediments. *Journal of Foraminiferal Research*, 18: 344–349.

- , 1995. Recolonisation by deep-sea benthic foraminifera: possible substrate preferences. *Marine Micropaleontology*, 26: 65–74.
- LE FRIANT, A., HARFORD, C. L., DEPLUS, C., BOUDON, G., SPARKS, R. S. J., HERD, R. A. and KOMOROWSKI, J. C., 2004. Geomorphological evolution of Monserrat (West Indies): importance of flank collapse and erosion processes. *Journal of the Geological Society, London*, 161: 147–160.
- LE FRAINT, A., LOCK, E. J., HART, M. B., BOUDON, G., SPARKS, R. S. J., LENG, M. J., SMART, C. W., KOMOROWSKI, J. C., DEPLUS, C. and FISHER, J. K., 2008. Late Pleistocene tephrChronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc. *Journal of the Geological Society, London*, 165: 279–290.
- MACARTHUR, R. H. and WILSON, E. O., 1967. *The theory of island biogeography*. Princeton, N.J.: Princeton University Press.
- MACKENSEN, A. and DOUGLAS, R. G., 1989. Down-core distribution of live and dead deep-water benthic foraminifera in box cores from the Weddell Sea and the California continental borderland. *Deep-Sea Research*, 36: 879–900.
- MACKENSEN, A., SCHUMACHER, S., RADKE, J. and SCHMIDT, D. N., 2000. Microhabitat preferences and stable carbon isotopes of endobenthic foraminifera: clue to quantitative reconstruction of oceanic new production? *Marine Micropaleontology*, 40: 233–258.
- MESSENGER, R. W., HART, M. B., SMART, C. W., LENG, M. J., LOCK, E. J. and HOWARD, A. K., 2010. Pteropod faunas as indicators of Late Pleistocene climate change in the Caribbean Sea. In: Whittaker, J. E. and Hart, M. B. Eds., *Micropalaeontology, Sedimentary Environments and Stratigraphy: A Tribute to Dennis Curry (1912–2001)*, The Micropalaeontological Society, Special Publications, Geological Society, London, 17–28.
- MVO, Montserrat Volcano Observatory. [www.mvo.ms](http://www.mvo.ms)
- MURRAY, J. W., 1965. Significance of benthic foraminiferids in plankton samples. *Journal of Paleontology*, 39 (1): 156–157.
- MURRAY, J. W. and BOWSER, S. S., 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize 'living' foraminifera. *Journal of Foraminiferal Research*, 30 (1): 66–70.
- MURRAY, J. W., STURROCK, S. and WESTON, J., 1982. Suspended load transport of foraminiferid tests in tide- and wave-swept sea. *Journal of Foraminiferal Research*, 12 (1): 51–65.
- OHGA, T. and KITAZATO, H., 1997. Seasonal changes in bathyal foraminiferal populations in response to the flux of organic matter (Sagami Bay, Japan). *Terra Nova*, 9: 33–37.
- OLUGBODE, O. I., HART, N. B. and STUBBLES, S. J., 2005. Foraminifera from Restronguet Creek: monitoring recovery from the Wheal Jane Pollution Incident. *Geoscience in south-west England*, 11: 82–92.
- RATHBURN, A. E., PÉREZ, M. E., MARTIN, J. B., DAY, S. A., MAHN, C., GIESKES, J., ZIEBIS, W., WILLIAMS, D. and BAHIS, A., 2003. Relationships between the distribution and stable isotopic composition of living benthic foraminifera and cold methane seep biogeochemistry in Monterey Bay, California. *Geochemistry, Geophysics, Geosystems*, <https://doi.org/10.1029/2003GC000595>
- RAU, A. J., ROGERS, J., LUTJEHARMS, J. R. E., GIRAudeau, J., LEE-THORP, J. A., CHEN, M.-T., and WAELBROECK, C., 2002. A 450-kyr record of hydrological conditions on the Western Agulhas Bank Slope, south of Africa. *Marine Geology*, 180: 183–201.
- REID, R. P., CAREY, S. N. and ROSS, D. R., 1996. Late Quaternary sedimentation in the Lesser Antilles island arc. *Geological Society of America Bulletin*, 108: 78–100.
- SADRI, S., HART, M. B. and SMART, C. W., 2011. Foraminifera from the sea grass communities of the proposed Marine Conservation Zone in Tor Bay. *Geoscience in South-West England*, 12: 269–277.
- SCHAFFER, C. T., 1982. Foraminiferal colonisation of an offshore dump site in Chaleur Bay, New Brunswick, Canada. *Journal of Foraminiferal Research*, 12: 317–326.
- SCHÖNFELD, J., ALVE, E., GESLIN, E., JORISSEN, F., KORSUN, S., SPEZZAFERRI, S. and Members of the FOBIMO group, 2012. The FOBIMO (FORaminiferal BIO-Monitoring) initiative – Towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies. *Marine Micropaleontology*, 94-95: 1–13.
- SEN GUPTA, B. K. and MACHAIN-CASTILLO, M. L., 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*, 20: 183–201.
- SHARIFI, A. R., CROUDACE, I. W. and AUSTIN, R. L., 1991. Benthic foraminiferids as pollution indicators in Southampton Water, southern England, U.K. *Journal of Micropalaeontology*, 10 (1): 109–113.
- SKIRBEKK, K., DIJKSTRA, N., JUNTILLA, J., STERNAL, B., BONDO PEDERSEN, K., FORWICK, M. and CARROLL, J., 2016. Biomonitoring polluted sediments in Arctic regions – possibilities and challenges using benthic foraminifera. Case studies from northern Norway. *Geophysical Research Abstracts*, 18: EGU2016–7362, 2016.
- SMART, C. W., 2002. Environmental applications of deep-sea benthic foraminifera. In: HASLETT, S. K., Ed., *Quaternary Environmental Micropalaeontology*, London: Arnold, 14–58.
- SMITH, K. L., BALDWIN, R. J., KAUFMANN, R. S. and STURZ, A. [Editorial], 2003. Ecosystem studies at Deception Island, Antarctica: an overview. *Deep-Sea Research II*, 50: 1595–1609.
- STOUFF, V., GESLIN, E., DEBENAY, J.-P. and LESOURD, M., 1999. Origin of morphological abnormalities in *Ammonia* (Foraminifera); studies in laboratory and natural environments. *Journal of Foraminiferal Research*, 29 (2): 152–170.
- TROFIMOVS, J., AMY, L., BOUDON, G., DEPLUS, C., DOYLE, E., FOURNIER, N., HART, M. B., KOMOROWSKI, J. C., LE FRIANT, A., LOCK, E. J., PUDSEY, C., RYAN, G., SPARKS, R. S. J. and TALLING, P. J., 2006. Submarine pyroclastic deposits formed at the Soufrière Hills volcano, Montserrat (1995-2003): What happens when pyroclastic flows enter the ocean? *Geology*, 34 (7): 549–552.
- TROFIMOVS, J., FISHER, J. K., MACDONALD, H. A., TALLING, P. J., SPARKS, R. S. J., HART, M. B., SMART, C. W., BOUDON, G., DEPLUS, C., KOMOROWSKI, J.-C., LE FRIANT, A., MORETON, S. G. and LENG, M. J., 2009. Evidence for carbonate platform failure during rapid sea-level rise: ca 14,000 year old bioclastic flow deposits in the Lesser Antilles. *Sedimentology*, 57: 735–759.
- WALL-PALMER, D., COUSSENS, M., TALLING, P. J., JUTZELER, M., CASSIDY, M., MARCHANT, I., PALMER, M. R., WATT, S. F. L., SMART, C. W., FISHER, J. K., HART, M. B., FRAASS, A., TROFIMOVS, J., LE FRIANT, A., ISHIZUKA, O., ADACHI, T., ALJAHDALI, M., BOUDON, G., BREITKREUZ, C., ENDO, D., FUJINAWA, A., HATFIELD, R., HORNBACH, M. J., KATAOKA, K., LAFUERZA, S., MAENO, F., MANGA, M., MARTINEZ-COLON, M., MCCANTA, M., MORGAN, S., SAITO, T., SLAGLE, A. L., STINTON, A. J., SUBRAMANYAM, K. S. V., TAMURA, Y.,

- VILLEMANT, B. and WANG, F., 2014. Late Pleistocene stratigraphy of IODP Site U1396 and compiled chronology offshore of south and south west Montserrat, Lesser Antilles. *Geochemistry Geophysics Geosystems*, 15 (7): 3000–3020.
- WALTON, W. R., 1952. Techniques for recognition of living foraminifera. *Contributions from the Cushman Foundation for Foraminiferal Research*, 3 (2): 56–60.
- WAŚKOWSKA, A., 2011. Response of Early Eocene deep-water benthic foraminifera to volcanic ash falls in the Polish Outer Carpathians: Palaeoecological implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 305 (1-4): 50–64.
- APPENDIX 1  
The benthic foraminiferal species mentioned in the text, including original names, are listed below in alphabetical order. Names follow Hayward et al. (2021).
- HAYWARD, B. W., LE COZE, F., VACHARD, D. and GROSS, O., 2021. World Foraminifera Database. Accessed at <http://www.marinespecies.org/foraminifera> on 15 May 2021. doi:10.14284/305.
- Ammodiscus incertus* subsp. *discoideus* Cushman 1917.  
*Amphistegina lessonii* d'Orbigny in Guérin-Méneville 1832  
*Bolivina albatrossi* Cushman 1922.  
*Bulimina aculeata* d'Orbigny 1826.  
*Bulimina striata* d'Orbigny in Guérin-Méneville 1832.  
*Cassidulinoides parkeriana* (Brady) = *Cassidulina parkeriana* Brady 1881.  
*Cibicidoides mundulus* (Brady, Parker and Jones) = *Truncatulina mundula* Brady, Parker and Jones 1888.  
*Cibicidoides robertsonianus* (Brady) = *Planorbulina (Truncatulina) robertsoniana* Brady 1881.  
*Cibicidoides wuellerstorfi* (Schwager) = *Anomalina wuellerstorfi* Schwager 1866.  
*Cribratomoides jeffreysii* (Williamson) = *Nonionina jeffreysii* Williamson 1858.  
*Cyclammina cancellata* Brady 1879.  
*Discammina compressa* (Goës) = *Lituola irregularis* var. *compressa* Goës 1882.  
*Eggerella bradyi* (Cushman) = *Verneuilina bradyi* Cushman 1911.  
*Eratidus foliaceus* (Brady) = *Lituola (Haplophragmium) foliaceum* Brady 1881.  
*Globocassidulina crassa* (d'Orbigny) = *Cassidulina crassa* d'Orbigny 1839.  
*Globocassidulina subglobosa* (Brady) = *Cassidulina subglobosa* Brady 1884.  
*Glomospira charoides* (Jones and Parker) = *Trochammina squamata* var. *charoides* Jones and Parker 1860.  
*Hansenisca soldanii* (d'Orbigny) = *Gyroidina soldanii* d'Orbigny 1826.  
*Haplophragmoides sphaeriloculus* Cushman 1910.  
*Hoeglundina elegans* (d'Orbigny) = *Rotalia (Turbinulina) elegans* d'Orbigny 1826.  
*Miliammina arenacea* (Chapman) = *Miliolina oblonga* var. *arenacea* Chapman 1916.  
*Nodulina dentaliniformis* (Brady) = *Lituola (Reophax) dentaliniformis* (Brady 1881).  
*Nonionella bradii* (Chapman) = *Nonionina scapha* var. *bradii* Chapman 1916.  
*Planulina ariminensis* d'Orbigny 1826.  
*Psammosiphonella discreta* (Brady) = *Rhabdammina discreta* Brady 1881.  
*Pullenia quinqueloba* (Reuss 1851)  
*Pyrgo fornasinii* Chapman and Parr 1935.  
*Reophax pihulifer* Brady 1884.  
*Reophax scorpiurus* Montfort 1808.  
*Reophax spiculifera* now called: *Reophax spiculifer* Brady 1879.  
*Rhabdammina abyssorum* Sars in Carpenter 1869.  
*Rhizammina algaeformis* Brady 1879.  
*Rotaliammina ochracea* (Williamson) = *Rotalina ochracea* Williamson 1858.  
*Saccammina sphaerica* Brady 1871.  
*Saccorhiza ramosa* (Brady) = *Hyperammina ramosa* Brady 1879.  
*Siphouvigerina ampullacea* (Brady) = *Uvigerina asperula* var. *ampullacea* Brady 1884.  
*Stainforthia fusiformis* (Williamson) = *Bulimina pupoides* var. *fusiformis* Williamson 1858.  
*Trochammina inflata* (Montagu) = *Nautilus inflatus* Montagu 1808.  
*Trochammina malovensensis* Heron-Allen and Earland 1929.  
*Uvigerina mediterranea* Hofker 1932.  
*Veleroninoides jeffreysii* (Williamson) = *Nonionina jeffreysii* Williamson 1858.