Reconstruction of light conditions within a submarine cave during the past 7,000 years based on the temporal and spatial distribution of algal symbiont-bearing large benthic foraminifers

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Abstract Coral reef cavities, crevasses, and caves are inhabited by cryptic communities. The sediments within the submarine Daidokutsu Cave (29 m water depth) on the fore-reef slope of Ie Island, Okinawa, Japan, preserve a fossil record of cryptic bivalve species over the past 7,000 years. The record suggests that infilling of cavities caused a progressive decrease in the exchange of water between the interior and exterior of the cave, resulting in a decline in food supply to the cave. To test this hypothesis, the light conditions within the cave were reconstructed from the spatial and temporal distributions of algal symbiont-bearing large benthic foraminifers, based on the assumption that infilling of reef cavities would have resulted in reduced light intensity within the cave. The results show that progressive darkening of the cave occurred by about 5,130 yr BP, synchronous with a weakening in water flow within the cave. This synchronicity indicates that infilling of cavities and narrowing of the cave entrance might cause declines in the exchange of water between the interior and exterior of the cave, as well as in light intensity within the cave. These resulted in a deficiency in food in the cave, thereby affecting the species composition of cavernicolous bivalves.

Keywords: algal symbiont-bearing large benthic foraminifer · cavernicolous bivalves · submarine cave · light conditions

1. Introduction

Cavities and caves are estimated to constitute between 60% and 75% of the total available surface of a coral reef (Jackson et al., 1971; Buss and Jackson, 1979; Logan et al., 1984) and between 30% and 75% of the bulk volume (Garrett et al., 1971; Ginsburg, 1983; Kobluk and van Soest, 1989). Such spaces are occupied by unique invertebrate communities (Jackson et al., 1971). Many workers have investigated the ecological and evolutionary significance of such communities (Jackson and Winston, 1982; Kobluk, 1988; Reitner and Gautret, 1996; Wörheide, 1998; Tabuki and Hanai, 1999; Kano and Kase, 2000; Kano et al., 2002; Kase and Kano, 2002; Ubukata et al., 2009) and seasonal to annual changes in environmental conditions within reef cavities (Gili et al., 1986; Fichez, 1990a, b, 1991; Harmelin, 1997; Lejeusne and Chevaldonné, 2005). In addition, several studies have examined the fluxes of various materials (e.g., dissolved oxygen, dissolved inorganic matter, dissolved organic matter, and bacterioplankton) in reef cavities (e.g., Ayukai, 1995; Yahel et al., 1998; Schffers et al., 2004; Van Duyl et al., 2002, 2006). For example, de Goeij and Van Duyl (2007) documented that coral cavities are a sink of dissolved organic carbon (DOC) which is produced by reefs and reef overlying waters, and possibly supplied from land-based sources. According to de Goeij et al. (2008), encrusting cryptic sponges are of quantitative importance in the removal of DOC in coral reef cavities.

Hayami and Kase (1992, 1993, 1996) and Kase and Hayami (1992) reported about 60 species of cavernicolous bivalves in tropical west-Pacific coral reefs, including Daidokutsu Cave, which is the focus of the present report. Most species are epifaunal or semi-infaunal suspension feeders, with no photosymbiotic or chemosymbiotic species being reported. However, no previous studies have investigated millennia-scale variations in the community of these organisms or their environment, with the exception of Kitamura et al. (2007a) and Yamamoto et al. (2009).

Kitamura et al. (2007a) examined the species composition of cavernicolous bivalves from the surface and two sediment cores (Cores 04 and 06) within Daidokutsu Cave of Ie Island, northwest of the main island of Okinawa, Japan (Figs. 1 and 2). The results showed that species living in the innermost area of the cave (the 1st group) became dominant in the past 5,000 yrs, whereas species living near the cave entrance (the 2nd group) declined in abundance during this time (Figs. 3 and 4). This finding indicates that the environmental conditions typically seen in the innermost cave area gradually spread across the cave. It is well known that the number of species and biomass show a progressive reduction toward the cave interior (e.g., Harmelin et al., 1985; Gili et al., 1986). This pattern has been explained by a decrease in the amount of organic matters provided by water flow from the open sea into the cave, with increasing distance from the cave entrance (Gili et al., 1986; Fichez, 1990a, b, 1991; Harmelin, 1997). Thus, Kitamura et al. (2007a) concluded that in the case of Daidokutsu Cave, faunal changes in the bivalve assemblage suggest a gradual increase in extent, over the past 5,000 yrs or more, of the cave area deficient in foods. In addition, the authors interpreted that the infilling of cavities had led to reduced exchange of water between the interior and exterior of the cave, resulting in a progressive decline in food supply.

Yamamoto et al. (2009) extended the record of the distribution of bivalves and sediment within Daidokutsu Cave up to 7,000 years BP, based on an analysis of a sediment core (Core 19; Fig. 5). The authors found brown sand-sized grains within sediments corresponding to the period 7,000–6,000 cal BP, and identified them as debris derived from a red soil layer formed in coastal zones around Ie Island. Moreover, the authors showed that the decline in abundance of very coarse sand-sized debris (1.0–2.0 mm in diameter; VCS debris) preceded that of coarse sand-sized debris (0.5–1.0 mm in diameter; CS debris) by about 550 years (Fig. 5), and regarded this difference as direct evidence of a weakening in water flow within the cave. The disappearance of VCS debris at about 6,500 cal BP was not accompanied by a change in bivalve assemblage, although the observed expansion of the 1st group coincided with the termination of CS debris at about 6,000 cal BP. Thus, an examination of the cause of the termination of CS debris would provide information that could be used to test the validity of Kitamura et al.'s (2007a) hypothesis that millennia-scale variations in cavernicolous bivalve assemblages were strongly influenced by a decline in food supply associated with the infilling of reef cavities.

However, there are two possible explanations of the termination of CS debris. The first interpretation assumes that the development of reef flats protected the coastal zones and thereby prevented erosion and transport of the red soil layer by high wave energy (Neumann, 1972; Hopley, 1984; Montaggioni, 2005). A second interpretation assumes that the infilling of cavities and narrowing of the cave entrance resulted in reduced water flow within the cave.

To evaluate the above interpretations, this study reconstructed temporal trends in light conditions within Daidokutsu Cave based on an analysis of the distributions of algal symbiont-bearing large benthic foraminifers (LBF) recovered from the surface and cored sediments within the cave. With infilling of the cavities and narrowing of the entrance, the interior of the cave would have become progressively darker. Distributions of living algal symbiont-bearing LBF are mainly controlled by temperature, light, water motions, substrate types, and nutrient levels (Hallock, 1999; Hohenegger, 2004; Renema, 2006; Uthicke et al., 2010). Of these parameters, light is the most important factor affecting depth distributions of algal symbiont-bearing LBF (e.g., Hallock, 1999; Hohenegger, 2004). Previous studies have provided a detailed account of the depth distribution of LBF around Sesoko Island, which is located 10 km southeast of Ie Island (Fig. 1; Hohenegger, 1994; Hohenegger et al., 1999; Yordanova and Hohenegger, 2002). This database in the same physico-chemical oceanographic setting enables us to reconstruct the light conditions within the cave.

Although many studies have examined the species compositions of benthic foraminifers within littoral and anchialine caves (Denitto et al., 2007; van Hengstum, 2008, 2009a, b), we are unaware of any published studies that have searched for millennia-scale variations in the species composition of LBF in completely submerged marine caves. This study is the first to describe the taxonomic composition and temporal-spatial distribution of algal symbiont-bearing LBF in submarine caves.

2. Study area

Daidokutsu Cave is located on the northeastern coast of Ie Island, Okinawa, Ryukyu Island Arc (Fig. 1A, B). The cave's entrance lies in about 19 m water depth on the fore-reef slope, and is roughly 18 m wide and 2 m high. The interior of the cave is very dark, 40 m long, and deepens abruptly inward to a maximum depth of 29 m (Fig. 1C). The floor near the cave entrance is covered with cobbles and boulders, while the floor of the interior is covered by calcareous sand and mud (Fig. 2). Kitamura et al. (2007a) divided the surface sediments in the interior into three facies (Fig. 2); Facies 1 is gray calcareous sand that occurs close to the entrance, Facies 2 is gray calcareous mud that occurs in the inner part of the cave, and Facies 3 is calcareous sand containing the skeletons of partly encrusted coralline sponges, which occurs in patches within Facies 2.

Water temperature inside the cave ranges from 29°C (August) to 21°C (February), showing similar seasonal variations to that observed at 30 m depth in the open sea around Okinawa (Kitamura et al., 2007b; Kitamura and Yamamoto, 2009). If we accept the sea-level curve proposed by Fairbanks (1989), Bard et al. (1996), and Toscano and Macintyre (2003), the cave was possibly completely submerged by about 8,000 yr BP. Sea level has remained at its present height during the past 7,000 yr (Montaggioni, 2005).

3. Materials

3.1. Sediments from the cave floor and reef slope

Kitamura et al. (2007a) examined the cavernicolous bivalve assemblage in surface sediments (uppermost 5 cm) collected at six sites within Daidokutsu Cave (a–f; Fig. 2). In the present study, we documented the LBF assemblage in these samples, as well as in the uppermost 5 cm of cored sediments (Core 04) collected from the innermost cave area (Fig. 2). For comparison, we also analyzed the LBF assemblage in a surface sediment sample collected from the reef slope (46.2 m below sea level; Fig. 1) and a living LBF assemblage in the surface sediment sample (70 g in weight) from site 1, which was located close to site b (Fig. 2).

The cavernicolous bivalves *Cosa kinjoi* and *Parvamussium crypticum* (1st group) are found within surface sediments at three sites (d–f) in the innermost cave area, while *Cosa waikikia* and *Hiatella* sp. aff. *H. orientalis* (2nd group) are observed within surface sediments at four sites (a–d) near the cave entrance (Kitamura et al., 2007a) (Fig. 3). According to Yamamoto et al. (2009), a very small amount of debris (less than one grain per 12.5g) from the red soil layer is recognized in surface sediments at three sites in the cave (d–f), but is not found in surface sediments at the other three sites (a–c) in the cave and on the reef slope.

3.2. Cored sediments

As noted above, Kitamura et al. (2007a) and Yamamoto et al. (2009) investigated temporal changes in the cavernicolous bivalve assemblage within three sediment cores. In the present study, we examined the LBF assemblage in Cores 06 and 19.

Core 06 (148 cm length) can be divided into a lower part, consisting of yellow calcareous mud (>22 cm length), and an upper part consisting of gray calcareous mud (approximately 126 cm length) (Kitamura et al., 2007a) (Fig. 4). The sharp boundary between the two parts is estimated to represent an age of about 5,450 cal BP. The gray calcareous mud is interpreted to have been deposited continuously at a sedimentation rate of ca. 21.1 cm/kyr. The ^{14}C ages of samples obtained from the lower part of the core fall within a narrow range from 5,980 to 5,060 cal BP, showing a non-linear relationship with depth (Fig. 4). Accordingly, Kitamura et al. (2007a) considered the possibility that the sediment in the lower part originated as a sediment gravity flow. CS debris occurs sporadically in Core 06, while VCS debris is not found (Fig. 4). Molluscs of the 1st group show a rapid increase in abundance immediately above the boundary between the yellow and gray calcareous muds. The species of the 2nd mollusc group show a decrease in abundance at about 2,200 cal BP.

Core 19 preserves a record of fossils and sedimentation over the past 7,000 years (Yamamoto et al., 2009). The sediment in the core shows a fining-upward trend, and is divided into an underlying gray calcareous sand (233–178 cm depth) and an overlying gray calcareous mud (178–0 cm depth) (Fig. 5). The sedimentation rate is estimated to be 41.7 cm/kyr between 233 and 153 cm depth, and 28.9 cm/kyr between 153 and 0 cm depth (Fig. 5). The VCS debris from the red soil layer is only found in the lower part of Core 19 (Fig. 5), and the abundance of the debris (the number of grains per gram of sediment) decreases upward from 0.6/g at 233 cm depth to <0.1/g at 203 cm depth. The abundance of CS debris decreases upward from 10/g at 233 cm depth to <1/g at 180 cm depth. Two species of the 1st mollusc group (*Cosa kinjoi* and *Parvamussium crypticum*) occur almost continuously after the termination of CS debris at about 6,000 cal BP (Fig. 5), while two species of the 2nd mollusc group (*Cosa waikikia* and *Hiatella* sp. aff. *H. orientalis*) show an upward decrease in abundance from about 72 cm depth.

4. Methods

Foraminifer tests were picked from the >0.5 mm size-fraction of surface and cored sediment samples. For Core 06, we analyzed foraminifer tests from samples collected at 1 cm intervals. The surface sediment sample from site 1 was stained with a rose Bengal solution (1 g L^{-1} of water), washed three times to remove surplus stain, and dried at 60°C. From >0.5-mm size fraction of the residue, all stained foraminiferal specimens with well-preserved test surfaces were identified as alive when collected, and isolated.

Foraminifer tests were identified to the lowest taxonomic level and the number of individuals was counted for each taxon. Taxonomic identifications were based on Hatta and Ujiié (1992a, b), Yordanova and Hohenegger (2002), and Renema and Hohenegger (2005).

We calculated the relative abundance (%) of foraminifer species in surface sediment samples. The stratigraphic distribution of each species in the cored sediments is expressed as abundance (the number of specimens per gram of sediment) (Supplemental Tables 1 and 2).

To find sediment sample groups with similar taxonomic composition, Q-mode cluster analysis was performed on log-transformed, relative abundance data of foraminifer taxa using a group-average linking method. For Cores 06 and 19, the top 25-most common taxa were used for analysis, to exclude occurrence of rare species from the data matrix. A Bray-Curtis dissimilarity coefficient was used to calculate a similarity matrix of taxonomic composition among samples. The multivariate analysis and the Bray-Curtis dissimilarity coefficient were computed using the software PRIMER Ver. 5 (PRIMER-E Ltd., England).

5. Results

A total of 61 taxa were identified from surface sediments in the submarine cave and on the fore-reef slope (Fig. 6; Table 1). Q-mode cluster analysis demonstrated that living LBF assemblage was clearly distinct from the dead assemblages in surface sediments (Supplemental Fig. 1). The dead assemblages could be divided into two subassemblages. One subassemblage was found in the innermost cave area (sites d-f, and Core 04). The sub-assemblage is dominated by *Amphistegina bicirculata*, *Calcarina mayori*, *Eponides repandus*, *Siphoniferoides siphonifera*, and *Rosalina petasiformis*. Another subassemblage was found near the cave entrance and on the fore-reef slope (sites a-c, and fore-reef slope). The subassemblage was dominated by *Amphistegina lessonii*, *A. bicirculata*, *E. repandus*, *S. siphonifera*, and *Planorbulina mediterranensis*. Most symbiont-bearing species in the dead assemblages such as *Amphistegina lobifera*, *A. lessonii*, *Heterostegina depressa*, and *Sorites orbiculus* were found mainly near the cave entrance and the fore-reef slope, whereas *A. bicirculata* and *C. mayori* occupied the innermost part of the cave (Fig. 7).

The living LBF assemblage in surface sediments from site 1 was dominated by non-symbiotic *E. repandus* and *Lenticulina* spp. (Fig. 6; Table 1). Many individuals of *A. bicirculata* and a few individuals of *C. mayori* and *H. depressa* were found as living in surface sediments from site 1. We found no stained individuals of *A. lessonii*, *A. lobifera*, and *S. orbiculus*.

A total of 38 and 78 taxa were identified from Cores 06 and 19, respectively. LBF assemblages from the two cores were dominated by *A. bicirculata*, *E. repandus*, *Quinqueloculina lamarckiana*, and *S. siphonifera*. Results of Q-mode cluster analysis demonstrated only one large cluster for the Core 06 data (Supplemental Fig. 2), suggesting that LBF assemblages in the vicinity of Core 06 were generally stable over time. *Amphistegina bicirculata* was commonly found throughout Core 06, whereas *A. lessonii*, *H. depressa*, *C. mayori*, and *S. orbiculus* occurred sporadically (Fig. 4; Supplemental Table 1). We did not find *A. lobifera* in Core 06. In contrast, three major clusters could be recognized for the Core 19 data, being correlated to samples from the lower (149-233 cm), middle (70-187 cm) and upper (0-135 cm) parts of the core (Supplemental Fig. 3). *Amphistegina lobifera*, *A. lessonii*, *H. depressa*, and *S. orbiculus* were commonly found in the lower part (233–151 cm depth), but were rare in the upper 150 cm, which was deposited after around 5,130 cal BP (Fig. 5; Supplemental Table 2). *Sorites orbiculus* was abundant within the horizon from 73 to 68 cm depth, and *Calcarina mayori* was relatively rare between 233 and 170 cm depth. *Amphistegina bicirculata* showed a gradual increase in abundance between 233 and 210 cm depth, and was predominant throughout the interval between 210 and 60 cm depth before showing a gradual upward decrease in abundance from 60 cm depth.

6. Discussion

Large benthic foraminiferal assemblages from surface and cored sediments inside the cave are composed of diverse heterotrophic and algal symbiont-bearing mixotrophic taxa. Algal symbiont-bearing mixotrophic taxa are characterized by species adapted to hard substrates in a low-light condition (e.g., the deeper part of the euphotic depths). It is notable that species adapted to soft (sandy) substrates in the low-light condition such as *Dendritina* spp., *Parasorites orbitolitoides*, *Amphistegina radiata*, *Amphistegina papillosa*, *Nummulites venosus*, and *Operculina complanata* (Hohenegger, 2004) were rare or absent. This was possibly because of the lack of sandy area particularly in the inner part of the cave and of relatively high-light conditions near the cave entrance.

In Core 19, *A. lobifera*, *A. lessonii*, *H. depressa*, and *S. orbiculus* show a decrease in abundance from at least 7,000 cal BP and occur only sporadically after about 5,130 cal BP, which corresponds to the upper 150 cm in the core (Fig. 5). *Amphistegina lobifera* inhabits turf algae that grow on high-energy reef crests throughout the Ryukyu Islands (Hohenegger, 1994; Iryu et al., 1995; Fujita, 2004), but rapidly decreases in abundance down to 20 m water depth, and is not found below 30 m depth (Hohenegger et al., 1999; Yordanova and Hohenegger, 2002; Hohenegger, 2004). Therefore, favorable water depths for this species are shallower than 15 m (Yordanova and Hohenegger, 2002). The optimal conditions for *A. lessonii* are found in water depths of 15–20 m with no substrate preference (Hohenegger, 2004; Renema, 2006): it is rare at the reef edge and is not found at water depths exceeding 75–80 m (Yordanova and Hohenegger, 2002). The maximum abundance of *S. orbiculus* occurs on hard substrates (in particular, macroalgae; Hohenegger, 2004; Renema, 2006) of reef slopes at 15 m depth; after a strong decrease in abundance down to 40 m depth, individuals are extremely rare at 50 m (Yordanova and Hohenegger, 2002).

Given that the present sea level has remained approximately constant for the past 7,000 years, the interior of Daidokutsu Cave (29 m depth) during this period has been much darker than 30 m water depth in the open sea. Therefore, there is no doubt that the interior of cave has been an unsuitable environment for *A. lobifera*, *A. lessonii*, and *S. orbiculus*. This is consistent with the absence of living individuals of these species from surface sediments at site 1 (Fig. 6; Table 1). However, many of their well-preserved empty tests occur in surface sediments within the cave at sites near the entrance (sites a–c) (Fig. 7) as well as in Core 19 (Fig. 5). Since this preservational state indicates short transport distances from the habitats of *A. lobifera*, *A. lessonii*, and *S. orbiculus*, these species are interpreted to live on hard substrates of cobbles and walls near the entrance of the cave at 19 m depth. Thus the upward decreasing trend in *A. lobifera*, *A. lessonii*, and *S. orbiculus* within Core 19 is explained by a decline in light intensity and/or weakening of water flow within the cave. The similar stratigraphic distributions of these species and CS debris (Fig. 5) indicates that termination of the supply of debris was caused mainly by a weakening of water flow within the cave, rather than a reduction in sediment supply from paleosols and terrigenous sediments deposited in coastal zones. Both *S. orbiculus* and CS debris are abundant in the horizon from 73 to 68 cm depth, implying that sediment reworking, although not significant, occurred at about 2,530 cal BP.

There exists a clear difference in the spatial and stratigraphic distributions of *H. depressa* and *C. mayori* within Daidokutsu Cave. The distribution of *H. depressa* is similar to that of *A. lobifera*, whereas the distribution of *C. mayori* is similar to that of *A. bicirculata* in Core 19, as shown below (Figs. 5 and 7). The two species show similar distributions around Sesoko Island (Yordanova and Hohenegger, 2002) as well as other area in the Ryukyus (Fujita, 2004), Indonesia (Renema, 2006) and inshore reefs of the Great Barrier Reef (Uthicke et al., 2010). *Heterstegina depressa* is rare near the reef edge, but its abundance shows a sudden increase at 10 m depth. The maximum abundance is found at 25 m depth, below which a gradual decrease in abundance occurs to 50 m depth; the deepest individuals occur at 95 m (Yordanova and Hohenegger, 2002). *Calcarina mayori* also lives in a wide range of water depths (10–70m), although its optimal depth is around 30 m (Hohenegger, 2004).

The above findings indicate that the difference between the two species in terms of their temporal and spatial distributions within the cave cannot be explained by light intensity alone. One possible interpretation is microhabitat differences between the two species. Although the two species prefer hard (macroalgae and reef rubble) substrates (Hohenegger, 2004; Renema, 2006), *Heterostegina depressa* is also found on sand (Hohenegger et al., 1999). *Heterostegina depressa* is characterized by weaker attachment than *C. mayori*. Thus, *H. depressa* avoids settling in exposed smooth surfaces to resist entrainment by hydrodyanimcs (Fujita, 2004), whereas *C. mayori* can attach to the smooth surface of hard substrates (Hohenegger et al., 1999). *Heterostegina depressa* also shows a clear preference for horizontal or oblique surfaces, and tends to avoid vertical surfaces (Renema, 2006). These observations suggest that *H. depressa* can live on reef rubble and calcareous sands on gentle slopes near the cave entrance, while *C. mayori* can live attached to roofs and vertical walls inside the cave. Another possible interpretation is space competition proposed by Hohenegger (2004), which showed that the density of *H. depressa* was suppressed by the co-occurrence of *C. mayori*.

Amphistegina bicirculata occurs continuously within the sediment from both the central part of Daidokutsu Cave (Core 06) and the innermost part (Core 19) (Figs. 4 and 5). The species lives on hard, gravel and coarse sand substrates in water depths of 30–130 m (Yordanova and Hohenegger, 2002; Hohenegger, 2004), particularly favoring the lower part of the euphotic zone (optimal depth of 80 m; Yordanova and Hohenegger, 2002). Tests of *A. bicirculata* are found in the innermost part of the cave (Fig. 7), and five living individuals were found within the surface sediment at site 1 (Table 1). These findings suggest that the specimens of this species are indigenous, living on calcareous sand, skeletal remains of macroinvertebrates, roofs and walls inside the cave, and that the innermost part of the present-day cave is a favorable environment for survival of the species. The abundance of *A. bicirculata* in sediment from the inner area of the cave (Core 19) shows a gradual increase until 5,000 yr BP (Fig. 5). Considering a gradual increase in abundance of *A. bicirculata* and *C. mayori*, as well as decreases in abundance of LBF species commonly found near the cave entrance discussed above, the interior of the cave is considered to have become darker during the period leading up to 5,130 yr BP. The darkness corresponds to the light intensity at 50–70 m water depth in the open sea, which is based on the overlap range between the depth distributions of *A. bicirculata* and *C. mayori*.

Because the gradual darkening of the cave was synchronous with reduced inflow of material from the open sea (debris from the red soil layer), it is likely that the infilling of cavities and narrowing of the cave entrance occurred up to 5,130 yr BP, which were probably caused by the development of reef-front and fore-reef zones and the transport of cobbles and boulders to the entrance. The decline in light intensity led to a decrease in photosynthetic production within the cave. In addition, the reduction in water exchange between the interior and exterior of the cave appears to have resulted in a reduction in the supply of various materials into the cave (e.g., dissolved inorganic and organic matter, and bacterioplankton) that are essential for both heterotrophs and autotrophs. Therefore, the findings of this study support Kitamura et al.’s (2007a) hypothesis that the infilling of cavities and narrowing of the cave entrance caused a millennia-scale decline in food supply within the cave, thereby affecting the species compositions of cavernicolous bivalves.

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Figure captions

Figure 1 Location map of the submarine Daidokutsu Cave on Ie Island, west of Motobu Peninsula, Okinawa Island, Japan (A, B), and simplified transverse section through the cave (C).

Figure 2 Bathymetric map showing the locations of sampling points for surface sediments (a–f, 1) and cored sediments. Also shown is the distribution of surface sediment facies (see text for details).

Figure 3 Spatial distributions of selected cavernicolous bivalve species in Daidokutsu cave (modified after Yamamoto et al., 2009). Percentages are given relative to the total number of individuals of all bivalve species. The locations of sites a–f are shown in Fig. 2.

Figure 4 Columnar sections of submarine-cave sediment within Core 06, showing stratigraphic changes in lithology and carbonate content, and abundances of debris, dominant large benthic foraminifer species and cavernicolous bivalve species, along with depositional rates inferred from the ^{14}C ages of molluscs (modified after Yamamoto et al., 2009).

Figure 5 Columnar sections of submarine-cave sediment within Core 19, showing stratigraphic changes in lithology, carbonate and mud contents and abundances of debris, dominant large benthic foraminifer species, and cavernicolous bivalve species, along with depositional rates inferred from the ^{14}C ages of molluscs (modified after Yamamoto et al., 2009).

Figure 6 Relative abundances of dominant benthic foraminifer species (those that make up >3% of the total count in each sample; dead specimens except for site 1) in Daidokutsu Cave. The locations of sites a–f, 1, Core 4, and the fore-reef samples are shown in Figs. 1 and 2.

Figure 7 Spatial distributions of algal symbiont-bearing large benthic foraminifer species in Daidokutsu Cave. The locations of sites a–f, Core 4, and fore-reef samples are shown in Figs. 1 and 2.

Table 1 Census data of large benthic foraminifer species in surface sediments.

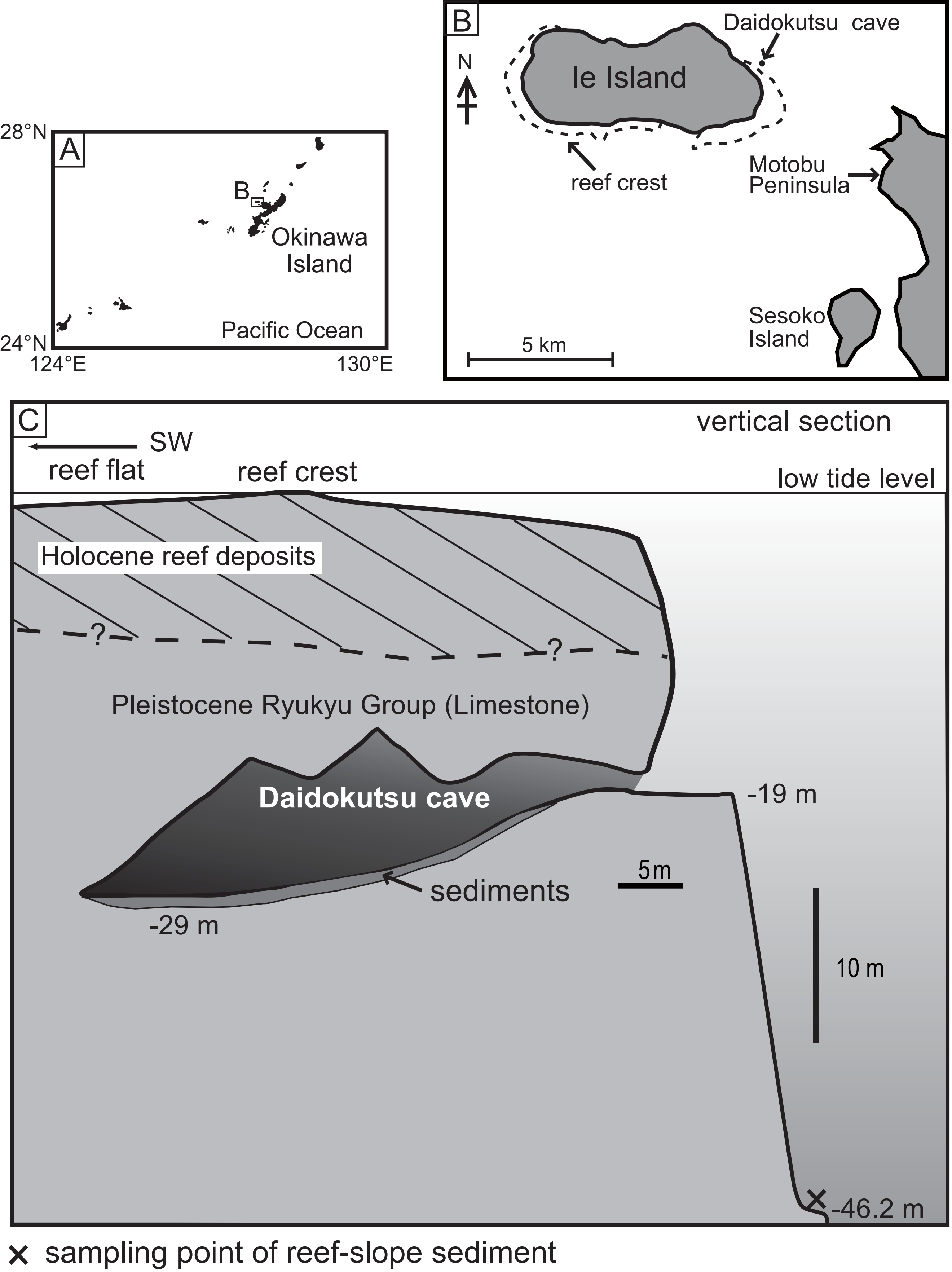
Supplemental Table 1 Census data of large benthic foraminifer species in Core 06.

Supplemental Table 2 Census data of large benthic foraminifer species in Core 19.

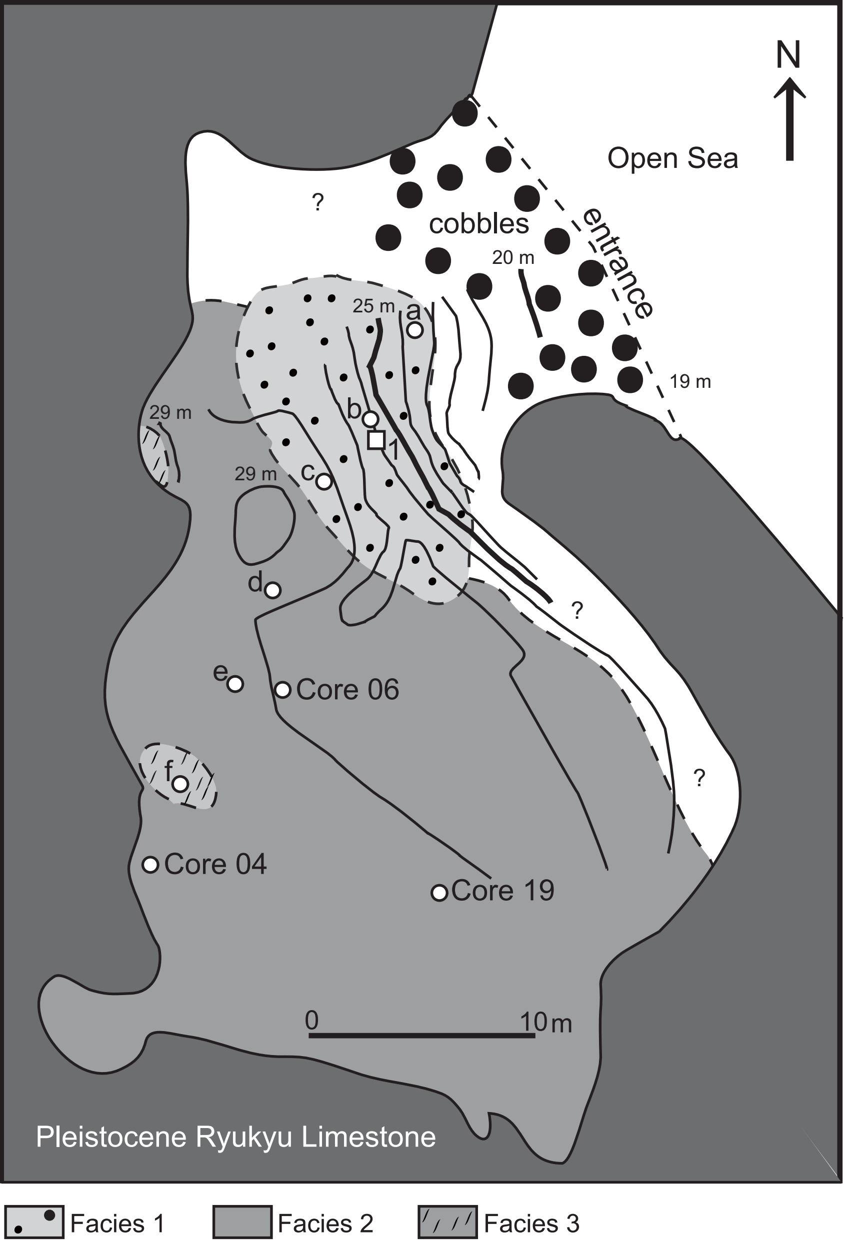
Supplemental Figure 1 Dendrogram of Q-mode cluster analysis of surface sediment samples in Daidokutsu Cave.

Supplemental Fig. 2 Dendrogram of Q-mode cluster analysis of submarine-cave sediment samples in Core 06.

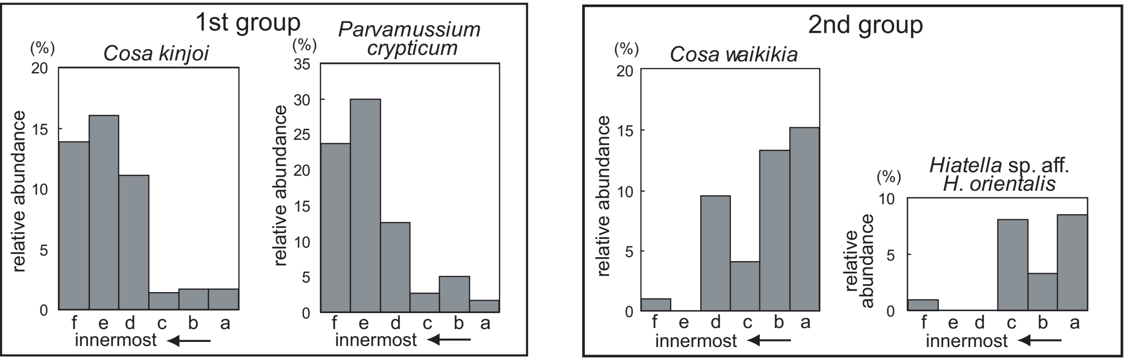
Supplemental Fig. 3 Dendrogram of Q-mode cluster analysis of submarine-cave sediment samples in Core 19.



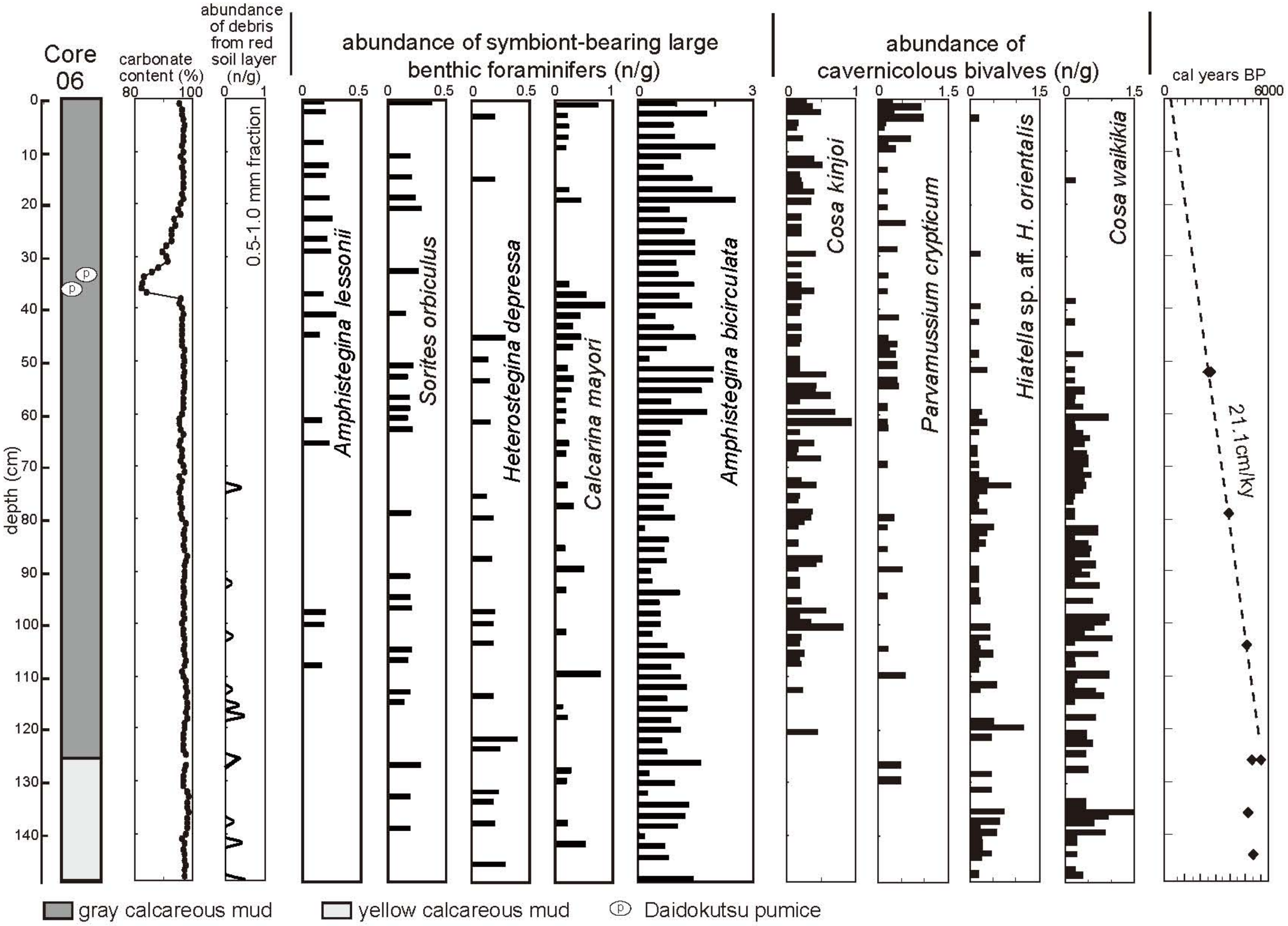
Omori et al Fig. 1



Omori et al. Figure 2



Omori et al. Fig. 3



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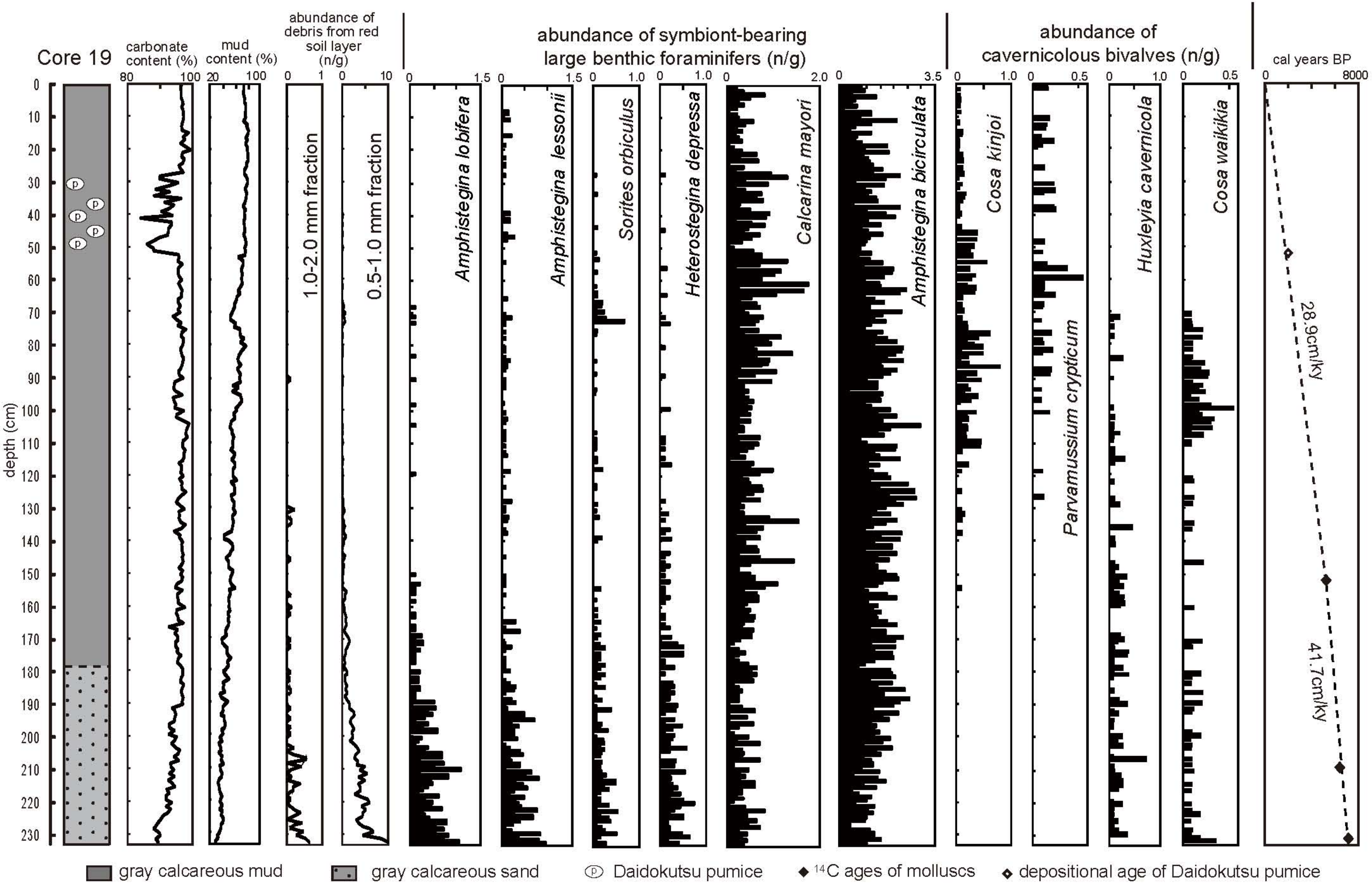

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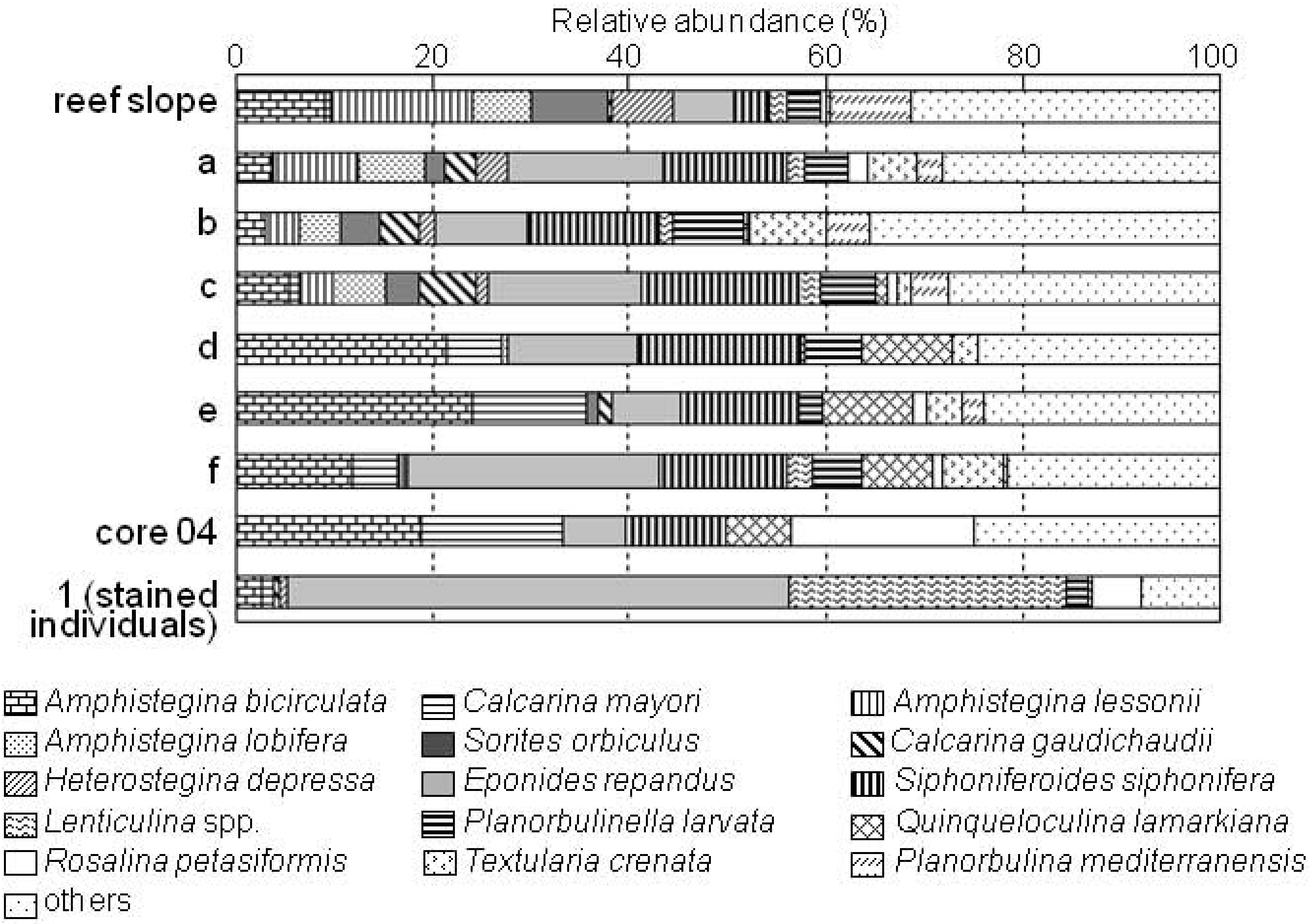

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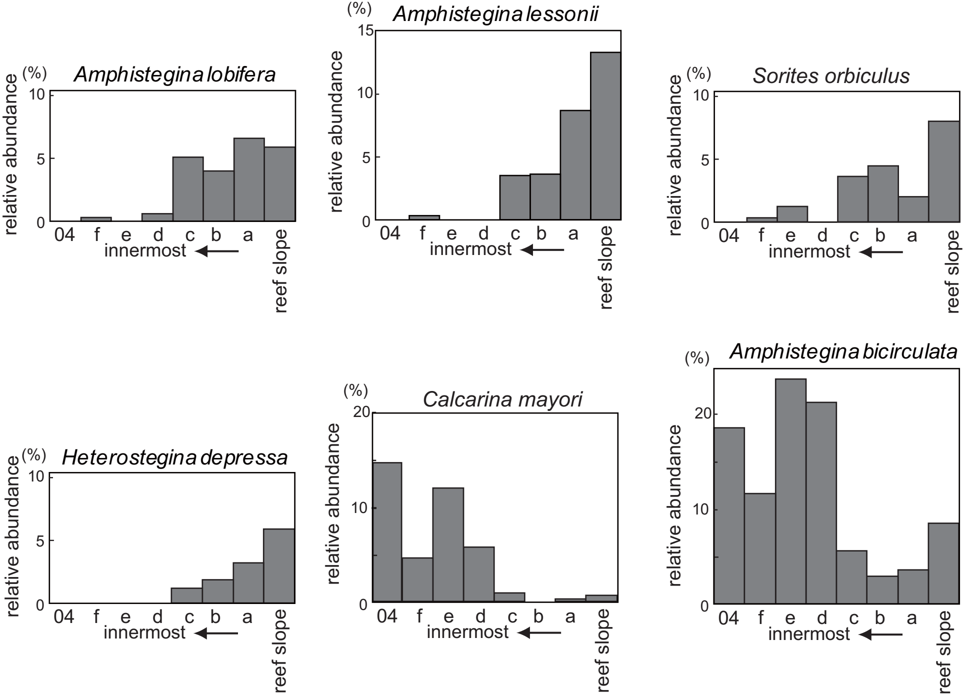
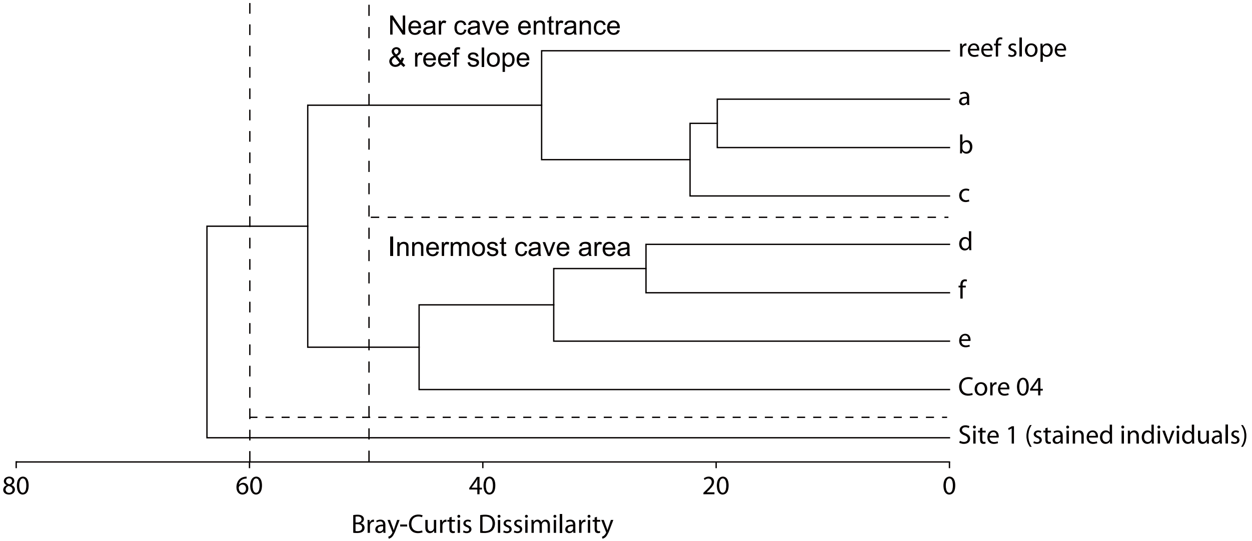


Omori et al. Fig. 7

Spiecies ＼ Site	reef slope	a	b	c	d	e	f	core 04	stained individuals （site 1）
Amphistegina bicirculata	29	15	8	14	34	20	41	9	5
Amphistegina lessonii	45	35	10	9			1		
Amphistegina lobifera	20	27	11	13	1		1		
Amphistegina papillosa	11	9	2						
Amphistegina radiata	17	10	7	2					
Amphistegina sp.	21	1	6	4			2		
Anomalinella rostrata	3	5	5	5			4		
Baculogypsina sphaerulata	2	4	6	10			1		
Baculogypsinoides spinosus	1		1						
Calcarina defrancii	3	5	4	4	1	2	3		2
Calcarina gaudichaudii	1	13	10	15		1			1
Calcarina hispida	1	2	1						
Calcarina mayori	2	1		2	9	10	16	7	2
Calcarina sp.	2	2	1						
Cibicides lobatulus	1	1			1	1			
Cibicidoides sp.				1	3		3		
Cribroeponides cribrorepandus				2	5	3	5	1	
Cymbaloporetta squammosa		3	3	1					
Cymbaroporetta tabellaeformis									1
Cymbaloporetta sp.	1	6	7	2					
Elphidiidae		1	2						
Eponides repandus	20	66	26	40	21	6	91	3	92
Glandulina ovula									3
Heterostegina depressa	20	13	5	3					1
Lenticulina spp.	5	8	4	5	1		10		51
Lingulinopsis sp.									1
Neoeponides sp.					1		2		
Neorotalina calcar				1	1		1		
Operculina ammonoides	1		1						
Pegidia dubia	4	5	3	2	6	2	15	2	4
Planorbulinella larvata	11	17	20	15	9	2	17		4
Planorbulina mediterranensis	26	12	12	9		2	2		
Planostegina operculinoides		2	1	2					
Rosalina petasiformis	3	8	1	2		1	4	9	9
Sphaerogypsina globulus		6	6	4	6	7	7		
Rotaliida				1		1	6	4	1
Amphisorus hemprichii	4	2	1	3					
Dendritina sp.			1						
Peneroplis pertusus		1					1		
Peneroplis planatus	2								
Peneroplis sp.	2								
Pyrgo denticulata					1				1
Pyrgo sp.		3	6	5	2				
Quinqueloculina bicarinata		1	1		1				
Quinqueloculina lamarkiana			1	3	15	8	26	3	1
Quinqueloculina parkeri	3		1						
Quniqueloculina rugosa	1								
Quinqueloculina sp.		1						1	
Sorites orbiculus	25	8	12	9		1	1		
Spiroloculina sp.	3	5	3		2	2	3		1
Triloculina kerimbatica			1		1				
Miliolida	1	2		1				2	
Siphoniferoides siphonifera	11	50	37	40	26	10	45	5	

Textularia agglutinans		7	6	3	3		13	1	
Textularia crenata	1	20	21	4	4	3	21		
Textularia dulpa		9	3	3	1		5		
Textularia foliacea			5	2		2			
Textulariida		5	2	2			1		
Acervulinidae	13	11	12	10	3		1		
Globigerinida		1					1		
Spirillina ? sp.		1						1	
unidentified	3	3			1		1		
total	319	407	276	253	159	84	351	48	180

Omori et al.
Supplemental Figure 1



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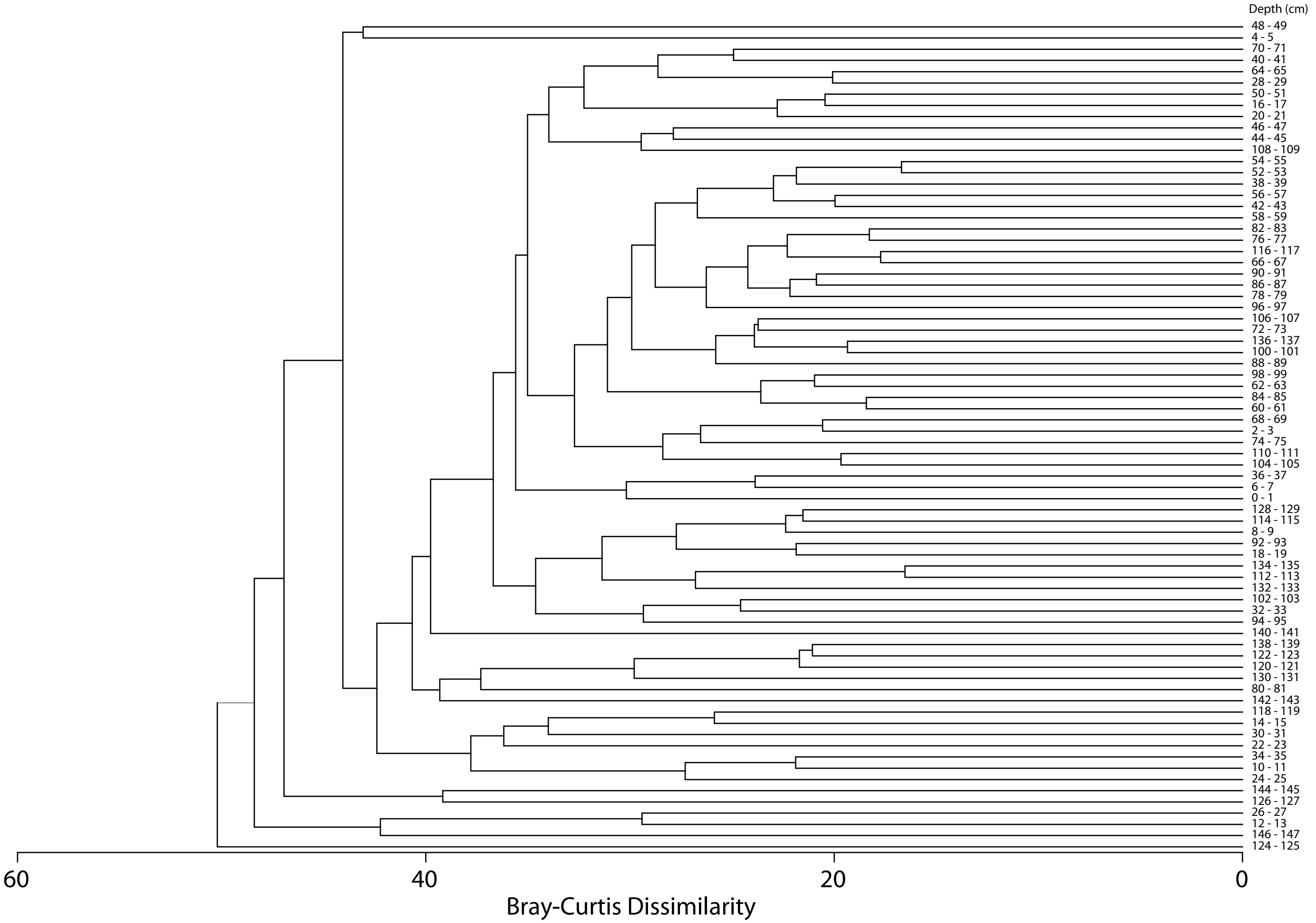
Supplemental Fig. 2



Omori et al.
Supplemental Fig. 3

Spiecies＼Samlpe No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Depth (cm)	0-1	2-3	4-5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21	22-23	24-25	26-27	28-29	30-31	32-33	34-35	36-37	38-39	40-41	42-43	44-45	46-47	48-49	50-51	52-53	54-55	56-57	58-59
Amphistegina bicirculata	5	9	4	4	11	6	3	7	8	11	3	5	6	7	6	4	4	6	6	8	3	6	10	5	2	9	12	12	5	10
Amphistegina lessonii	1	1			1		1	1		1		1		1	1				1		2		1							
Amphistegina papillosa																										1				1
Amphistegina radiata				1						2															1					
Anomalinella rostrata		1									1				1	1			1					2			1	1	1	2
Acervulinidae	4				4	1				2												1	3	1				1		
Baculogypsina sphaerulata					1	1														1										1
Calcarina gaudichaudii										1	1	1								2				2				1		
Calcarina mayori	4	1	1	1	1				1	2								1	3	5	3	2	3	2		1	2	2	1	1
Cibicidoides sp. A				1	1																							1		
Cibicidoides sp. B		1	1																						2		1	1	2	1
Cribroeponides cribrorepondus				1				3		1		2			1				4	1		2	2		1		5	3	3	4
Eponides repondus	2	7	3	4	5	1	3	1	3	4	6			2	5	5	9	1	5	8	5	8	4	8	7	5	19	15	9	9
Gemirospira sp.																							1				1			
Glandulina antarctica		1			1	2				3																				
Heterostegina depressa		1						1															2		1		1			
Lenticulina spp.											1						1			2		1				2	1	1	1	
Milliolida			2		1					1					2					1	1							1		
Neoeponides sp.								1								2				1			1		2			1	1	3
Neorotalia calcar													1										1	1		1	1		1	1
Pegidia dubia form A			3	1	2	1	1	1	1	3			1				2	2		5	2	2			2		1	2	2	1
Pegidia dubia form B								1		1					1								1					2		
Globigerinida							2													1				2			1	1		1
Planorbulinella larvata		2	2		4	2	1	2		1		1	2		1	2	1	2	3	5	2	1	3	4	2	1	3	1		
Pyrgo sp.										1					1		1		1	1	1		1	1		1		2	1	1
Quinqueloculina bicarinata																														
Quinqueloculina lamarkiana	6	6		3	5	4	2	3	3	5	4	5	4	1	3	10	1	4	4	29	9	8	15	7	5	3	14	18	6	5
Rosalina petasiformis	4	1																	1											
Rotallida	3	1		5		1	2	2	1	2	1				1	1		1	4	1	3		1			1	1	5	1	3
Siphoniferoioles siphonifera	8	7	1	4	11	3	1	3	5	7	6	3	3	1	3	3	3	2	8	11	12	4	5	5		5	17	12	5	5
Sorites orbiculus	2					1		1		1	1						1				1					1	1		1	1
Sphaerogypsina globulus	2	2	2	1	7				2	2	1	1	3				1		2	8	3	1	3	3	3	1	4	4	1	5
Spiroloculina sp. A	1	2		2			1			1				1					1	1					1			2		
Textularia agglutinans	3	2	1		2			1		2		1				1	1			1		1			3				2	1
Textularia crenata		2	2		1	1	2			1			1	1	1		2			3	1	1				1	3	2	1	
Textularia dupla	1	1																			1		2		1					
Texturalia foliacea		2			2												1						1						1	
Textulariida	1				1												1		1	2			3						2	2
unidentified																					2									
total	47	50	22	28	61	24	19	28	24	55	25	20	21	14	27	29	29	19	45	97	51	38	63	43	33	33	89	91	47	58

31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
60-61	62-63	64-65	66-67	68-69	70-71	72-73	74-75	76-77	78-79	80-81	82-83	84-85	86-87	88-89	90-91	92-93	94-95	96-97	98-99	100-101	102-103	104-105	106-107	108-109	110-111	112-113	114-115	116-117	118-119	120-121	122-123	124-125	126-127	128-129
7	4	3	4	4	2	4	6	4	5	1	5	4	4	2	2	6	3	3	3	2	4	6	5	7	9	4	10	4	5	3	3	2	1	5
1		1																1	1				1											
						1		1	1						1						1		1			1								
2	1	1			1			1			1		1			1	1		1	1	1	1	2		1	2	1					1		
1	1	1	1	1	1	1	1	1	1		3	1		2	1	2	1	1	2		2				2	1	4				2			
1			1	1		1		2		1	1		1	1	1	1	1	2		5	1		2	2	1	4	8	3	3	3	3		3	2
						1	2		1		2	1		1		2			1						1									
	1										1	1	1																					
1		1	1			1		2				1		3		1				1				5			1	1					1	1
2												2						1								1	2							
1	3		2			2	1	4	2	1	3	4	3	2					4	1		2	2		3			2		1				
1		2	1			1	1		3	1	2	1	3	4	1	1		7	2	3			1			3		2	1	3	4			
15	8	10	8	12	6	6	14	13	12	2	15	11	13	10	9	4	8	5	10	6	9	10	8	12	13	6	9	4	3	4	4	1	6	4
		1				1						1						2							1				1		1			
				1												1																		
1							1		1				1					1	1		1					1				2	1			
						1		2	2		2		1	2	1						2	1	1		1					1	3			
	1	1			1							1		1		1				1	1		1	1			1			1				1
2							1		1			6																						
		1			1			2				1		1	2		1				1			1									1	
1	1	1	1	1	3			3	1		3	1	2	1	2		2	1	1	1		1		1			3	1	1		2			
		2	1								2			2										1					2				1	
				1				1			2																	1						
1		2	4	2	3		2	1	3		5	2	1	3	1	1		1	1	1	2	3	1	2	1	7	1	1	3	2	2		4	2
	1	1				1						1				1			1	1			1											
												1						1					1			1								1
14	7	4	2	7	4	2	6	2	6	2	5	10	2	2	4	1	3	2	6	2		2	1	1	2	2	3	2	2				1	1
				1			2						1										1			2	1							1
2	1	1	1	2	1	2	1	2	1		5	1	5	3	3			2	1	3		2	2	3	1		2	2	3	2	3			
8	8	8	5	6	4	3	7	6	18	4	9	12	9	8	7	6	4	6	3	2	5	9	8	5	6	8	8	5	1	5	8	1	7	5
1	1								1						1		1	1				1	1			1	1						1	
3	1	1	2	1	3	5	2	2	2		2	2	2	1	4	1	1	3	1	1	7	1	2	9		3	5	4	1	2		1		2
1	1			3			1		1		1	1	1			1		1				2			1			2						
			1	2				1	2	1	2				1			2			1	3			2	1	1	1	1	1	1		3	1
		2		1		2	6	1			2			2		2	2			1	3	3	2		1	1	3				1		1	
		1		2			1	1			1			1	1			1					2	2			2	2		1	2		1	1
1				1								1		1							1	2											1	
	1			1				1				1	1	1		1			2			1			1		2		1					
																								1										
67	41	45	35	50	30	35	55	53	64	13	74	68	52	54	42	34	28	44	41	32	42	50	46	53	47	49	68	37	28	31	40	6	32	27

66	67	68	69	70	71	72	73	74
130-131	132-133	134-135	136-137	138-139	140-141	142-143	144-145	146-147
1	7	5	5	1	4	4		5
		1					1	
		1	2					
		1		1				
3	3		1	3	2			
			1		3			
1					1			1
2			1	1		1		
5	1	1	2	3		1		
4	8	6	14	8	7	3	8	6
						1		
1	1		1				1	
					1	1	1	
2								
		1		1				
3				1		1		1
							1	
	1				2			1
	1	1	1	2			2	1
					1			
	1		1		2	1		
	3	1	2					
	1	1						
1			1	3	2		1	
5	7	7	3	8	3	5	5	1
	1			1				
1		2	2	3	2	1	1	
		1			1			
	1	1	1	1	1	1	3	
1					2		1	1
1	1					2	1	
	2	1	1			1	1	
	1							
31	40	31	39	37	34	23	27	17

Spiecies＼Samlpe No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Depth (cm)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33
Amphistegina bicirculata	5	6	3	9	3	3	4	1	7	4	12	10	4	3	10	6	6	7	17	7	18	7	10	8	12	13	11	23	19	5	14	8	10
Amphistegina lessonii									1		1					2			1				1		1			1					
Amphistegina lobifera																																	
Amphistegina papillosa																1					1										1		
Amphistegina radiata																																	
Amphistegina sp.	2																																
Anomalinella rostrata															1								1				1						
Astacolus sp.																																	
Baculogypsina sphaerulata																															1		
Baculogypsinoides spinosus																																	
Calcarina defrancii	1	2	2		2		2		1	3	1	1		3		3	1		2	3	3	1		2			1	2	2	1	3		1
Calcarina gaudichaudii																					1						1						1
Calcarina hispida																																	
Calcarina mayori	1	2	5	3	1	2	1		1	1	3	3	1	2	1	2	3		1	2	6	2	6		3	1	8	13	4	7	1	3	6
Calcarina sp.				1																													
Cibicides lobatulus																															1		
Cibicidoides sp.												1					2				2	1				1	2	1	1				
Cribroeponides cribrorepandus				1								1							2	1		1			5	1	2	3		1	4	1	
Cymbaloporetta squammosa																																	
Elphidiidae																																	
Eponides repandus	1	2	1		1		1		4	1	1	1			1		1	5	5	4	5	1	2		1		2	6	5	3	2	6	9
Gemirospira sp.																																	
Heterostegina depressa																												1					
Lamarckina ventricosa																																	
Lenticulina spp.																1		1		1						1		1	1				
Lingulina carinata																																	
Lingulina sp.																																	
Neoeponides sp.			1																			1											
Neorotalina calcar																				1													
Operculina ammonoides																																	1
Palmula robusta																																	
Pegidia dubia		1							1	1			2	1	1	2	1	1	3		1		1		2	2	2	3	1		1	1	2
Planorbulina acervalis																																	
Planorbulinella larvata	1		3	3			1				1			1	1	2		3	1		2	1	1	1	2	1	1	5	1	1	1		1
Planorbulina mediterranensis								1									1					1											
Planostegina operculinoides				1																													
Rectobolivina sp.																																	
Rosalina petasiformis																												1					1
Sphaerogypsina globulus	1	3	1			1				1		1		2		1	2	3	2	1	1	1	1	2		1	5	2	3	2		4	2
Stomatorbina concentrica																																	
Stomatorbina sp.	1												1																				
Tretomphalus bulloides																																	
Rotaliida										1			1						3														
Alveolinella quoyi																																	
Amphisorus hemprichii																											1						
Dendritina sp.																																	
Glandulina antarctica																																	
Miliolinella circularis																																	
Miliolinella webbiana																																	
Nodobaculariella insignis																																	
Peneroplis pertusus																																	
Peneroplis planatus																																	

Peneroplis sp.																																	
Pseudohauerina involuta																																	
Pyrgo denticulata																																	
Pyrgo sp.																					1												1
Quinqueloculina bicarinata																																	
Quinqueloculina lamarkiana	2	2	4	4	1	1	2	4	1	1	1	2	2	1	2	3	2	6	6	4	9	1	1	7	3	3	4	6	3	5	5	6	10
Quinqueloculina parkeri																															1		
Quinqueloculina sp.																																	
Sorites orbiculus																												1					
Soritinae																																1	
Spiroloculina sp.	1										1			1	1				1	1		1	1						1				
Spirosigmoilina sp.																																	
Triloculina sp.																																	
Vertebralina sp.																																	
Miliolida																	1						1						1				2
Cylindroclavulina sp.							1													1													
Reophax ? sp.																																	
Siphoniferoides siphonifera	3	2	2	1	1	1		3	1	1	1	3	4	1	5	3	2	14	5	2	9	1	2	4	7	6	9	15	10	5	8	4	8
Textularia agglutinans		1		2	2	1				1	1					1	1	1	1	1	2	1	2		4	1	1	3	3	2			1
Textularia crenata	1		1	2							1							1	1				1	1	1		1	1			1	1	1
Textularia dupla											1	1					1						1			1		1				2	
Textularia foliacea																																	1
Textulariida																												1	1				
Acervulilnidae									1																								
Globigerinida																																	
Spirillina ? sp.										1							2				1	1						2					
unidentified																																	2
total of individuals	20	21	23	27	11	9	12	9	18	16	25	24	15	15	23	27	26	42	51	29	62	22	32	25	41	32	52	92	56	32	44	37	60

Spiecies＼Samlpe No.	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113
Depth (cm)	80-81	81-82	82-83	83-84	84-85	85-86	86-87	87-88	88-89	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-100	100-101	101-102	102-103	103-104	104-105	105-106	106-107	107-108	108-109	109-110	110-111	111-112	112-113
Amphistegina bicirculata	24	22	21	16	25	13	14	21	20	18	11	13	13	4	20	18	17	13	12	20	16	21	14	16	30	18	16	15	8	11	24	21	12
Amphistegina lessonii	1	1		1	2	1	1	1			1	1	1					1			1		1	1			1	1	1		1		1
Amphistegina lobifera				1							1								1						1								
Amphistegina papillosa	1	2	1	2		1			1	1	1									3							1				1	1	
Amphistegina radiata		1			1															1		1	1						1				
Amphistegina sp.									3		1	2									1		1	1	1		1			1			
Anomalinella rostrata	1		1	2			1	1			3	1	1									1			2	1		1	1		4	1	1
Astacolus sp.	2																															1	
Baculogypsina sphaerulata			1	2	3	1		2	1	2					1	2	2	3		2	1		1		3	1	1				1		
Baculogypsinoides spinosus															1													1					
Calcarina defrancii	2			3	1	2				1					1											1						1	
Calcarina gaudichaudii										1																			1				
Calcarina hispida					1			1																			1						
Calcarina mayori	6	13	6	8	9	6	2	10	6	2	10	3	3	5	4	5	6	5	5	4	5	2	4	2	3	3	2	6	2	7	6	4	2
Calcarina sp.			1									2										1											
Cibicides lobatulus																																	
Cibicidoides sp.	1		2	2	3	3		3	4	3	3				1		2	5	4	1	4		3	4	6	2	3	2	5	5	2	5	1
Cribroeponides cribrorepandus	11	3	3	13	5	7	8	9	4	6	4	3	7	4	4	3	2	7	6	4	4	4	2	2	5	9	6	1	8	2	12	7	9
Cymbaloporetta squammosa																																	
Elphidiidae																																	
Eponides repandus	15	10	13	14	11	8	4	13	12	13	22	3	13	12	6	9	6	6	7	10	12	8	12	8	13	16	12	9	14	8	18	16	9
Gemirospira sp.				1							1	1	1				1		1		1					3							
Heterostegina depressa	1									1										2									1	1		1	

Lamarckina ventricosa																																	
Lenticulina spp.			1		2	1		2	1	2	3	1		1	1	1	1			1		2									1		
Lingulina carinata																		1															
Lingulina sp.																																	
Neoeponides sp.	2	3				3		2	1				1				1							1				1			1		
Neorotalina calcar	1	2	4			2	2		4		2			1	1			1		3	1						1	1					
Operculina ammonoides							1																										
Palmula robusta																																	
Pegidia dubia	5	5	3	1	1		1	4	1	4	1	4	2	2			1		1	6	4	3	3	5	2	3		2	2	3	7	4	1
Planorbulina acervalis		1																															
Planorbulinella larvata	6	6	2	3	2	6	2	3	3	7	8		5	1	2	5	5	5	5	8	2	2	3	4	12	10	8	1	3	7	1	6	2
Planorbulina mediterranensis	1			1			1	1	1					2			2		1	1						1		1	1		2	2	1
Planostegina operculinoides				1						1	1																1						
Rectobolivina sp.																																	
Rosalina petasiformis				1	7	1	2	4	3	1	4				3	1				1	1					3		1	1		1		
Sphaerogypsina globulus	7	5	4	5	5	4	3	6	4	3	6	1	3	1			1	3	4	2	3	5	7	2	8	2	1	2	2	5	1	2	3
Stomatorbina concentrica											1		1	1																			
Stomatorbina sp.					1												1																
Tretomphalus bulloides									1	1	1										1			1								1	1
Rotaliida				2	2		2			1	2			2					1	2		1		1								2	2
Alveolinella quoyi																																	
Amphisorus hemprichii					1																												
Dendritina sp.																																	
Glandulina antarctica									1	1																							
Miliolinella circularis																																	
Miliolinella webbiana																																	
Nodobaculariella insignis																																	
Peneroplis pertusus																																	
Peneroplis planatus																																	
Peneroplis sp.																																	
Pseudohauerina involuta																																	
Pyrgo denticulata				1																													
Pyrgo sp.			1																	1	1									1		1	
Quinqueloculina bicarinata																										1			1				
Quinqueloculina lamarkiana	10	9	11	7	5	2	1	9	3	7	5	2	2	1	3	7	2	5	4	8	3	4	4	5	11	11	8	10	8	6	6	8	5
Quinqueloculina parkeri																																	
Quinqueloculina sp.																																	
Sorites orbiculus					1				1					1	1												1		1	1	1	1	
Soritinae																																	
Spiroloculina sp.	1		1	1			1	2		1		1	1	1	1		1	1		2	1		2	1	1	2				1			
Spirosigmoilina sp.																																	
Triloculina sp.																																	
Vertebralina sp.																																	
Miliolida				1	1			1		1													1				1						
Cylindroclavulina sp.																																	
Reophax ? sp.																																	
Siphoniferoides siphonifera	12	3	9	11	4	3	12	10	9	10	11	4	3	8	11	8	4	10	6	5	12	9	10	10	12	9	12	6	4	6	5	9	5
Textularia agglutinans		1						3	2		3												1					1	2	1	2		
Textularia crenata	3	3	2					2					2			1	1	1	1	1						1	1						1
Textularia dupla		1	4	1		1	1	1	1	1			3	1		1		1			1	1	1	1		1			1	2	1	2	
Textularia foliacea					1		2		1																					1	1		
Textulariida	1				2				1																			1					
Acervulilnidae	1				1	1		1	1			1	1	1			1		1		2				1	1		2	1	1	4		
Globigerinida				2			1	1		1	2			1								3				1	1		1	3	1	2	
Spirillina ? sp.																																	
unidentified				1	2	1	1	3	1	2	2		1	1	1	2	2	1	1		1	1						1		2		1	1

total of individuals	115	91	91	104	99	67	63	116	91	92	110	43	64	51	62	63	59	69	61	88	78	69	71	65	111	100	79	66	70	75	104	99	57

Spiecies＼Samlpe No.	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193
Depth (cm)	160-161	161-162	162-163	163-164	164-165	165-166	166-167	167-168	168-169	169-170	170-171	171-172	172-173	173-174	174-175	175-176	176-177	177-178	178-179	179-180	180-181	181-182	182-183	183-184	184-185	185-186	186-187	187-188	188-189	189-190	190-191	191-192	192-193
Amphistegina bicirculata	11	15	12	14	17	22	11	17	17	21	20	13	20	12	20	21	12	9	7	20	20	21	13	22	14	25	16	16	25	22	21	11	22
Amphistegina lessonii					3		1	4				1	2	1		1	1	1	1	2			1	2	3	3	1		2	3	1	1	5
Amphistegina lobifera			1	1			1	1		2	1	3	1	2	1	1	1	1			2		2	2		2	1	1	1	5		5	4
Amphistegina papillosa		1				1		1		3		4	2			1						1			1		2						
Amphistegina radiata					2	2		1			1	2	1			3			2	2		2	2	1	2						1		2
Amphistegina sp.				2		1		1				1			1					1				1							2	1	2
Anomalinella rostrata	1	2	1	3	2	3	3	1	1	2	1	1	2	2	3	1	1		2	2	1	1	1	2	1	4			2	3	2	2	1
Astacolus sp.			1																	1													
Baculogypsina sphaerulata	1			2														1					1	1									
Baculogypsinoides spinosus												1											1							1			
Calcarina defrancii																														1			
Calcarina gaudichaudii																																	
Calcarina hispida											1				1		1		2						1								
Calcarina mayori	4	5	5	3	3	5	5	5	2	1		2	3	2	1	2	4	6	5	6	5	6	1	2	3	2	2	2		3	5		4
Calcarina sp.		1			1				1												1												
Cibicides lobatulus		1		1					2			1	1			1					1	1			1	1			1		1	3	
Cibicidoides sp.	3	3	5	4	4	6	1	5	10	5	1	14	3	3	3	3	6	7	1	5	6	4	3	9	6	5	4	3	4	5	7	7	7
Cribroeponides cribrorepandus	2	4	9	7	4	5	8	8	13	6	16	19	12	11	21	3	8	9	9	7	8	9	7	10	11	7	12	11	12	11	12	11	11
Cymbaloporetta squammosa																																	
Elphidiidae																																	
Eponides repandus	13	16	19	12	21	17	21	20	30	26	24	28	19	21	33	24	15	13	17	19	41	23	22	29	23	27	26	17	16	16	40	27	23
Gemirospira sp.	1				1		2	1		1					2	2			1		1		4	2		3				1	1	2	
Heterostegina depressa			1	1		1	2			2		4	5		5		1	1	3		1			3	3	2	3	2	2	1	4	3	1
Lamarckina ventricosa																						1					1			1			
Lenticulina spp.	1	1		1					1		1		1	1	1	3	1			3	2	1		2	1	1			1	4	2	1	1
Lingulina carinata																																	
Lingulina sp.																																	
Neoeponides sp.	1					1													1			1						1					1
Neorotalina calcar			2				1	1		1	3	3		1	3					1					1	1					1		
Operculina ammonoides							2			1		1	1					1			2		1	1	1		2	1	1	1		1	2
Palmula robusta																																	
Pegidia dubia	1	2	1	2	3	2	1	2	6	3	2	4	4	2	4	3	1	2	2	3	5	1	5	2	2	4	2	4	1	4	4	3	5
Planorbulina acervalis																																	
Planorbulinella larvata	4	5	3	4	4	9	3	8	3	7	5	9	5	4	4	4	3	4	5	8	6	4	4	2	9	9	4	1	2	4	5	6	9
Planorbulina mediterranensis										2	3		1	1	1	3	1	1	2		1		1					1		1	4		
Planostegina operculinoides			1			1	1			1		2		1		1				2	2	2				1	1				1		1
Rectobolivina sp.																																	
Rosalina petasiformis	2	1	2	4	1	2	1	5	6	1	2	2	4	1	5	3	1	1	3	2	4	1		2	1	3	1		3	4	3	2	2
Sphaerogypsina globulus	2	4	1		5	2	2	4	5	3	1	3	2	5	2	5	4	5	3	8	6	6	4	2	8	4	3	7	5	10	5	1	5
Stomatorbina concentrica							1																										
Stomatorbina sp.																						2											
Tretomphalus bulloides							1																							1			
Rotaliida				2		1				1	2	1						1		2		1			1		1	2	1		1	4	
Alveolinella quoyi																																	
Amphisorus hemprichii					1	1						1			1					1		2								1			3
Dendritina sp.												1																					
Glandulina antarctica																																	
Miliolinella circularis																																	
Miliolinella webbiana																																	
Nodobaculariella insignis																																	

Peneroplis pertusus																																	
Peneroplis planatus																																	
Peneroplis sp.																																	
Pseudohauerina involuta																																	
Pyrgo denticulata													2																			1	
Pyrgo sp.										1	1				1	1		1	1				1	2	1	1		1				1	1
Quinqueloculina bicarinata	1	3	1	1			2		3	2	3	1	4	2	1	2		2		2		1	1	2	2	1	3	1		2	3	3	1
Quinqueloculina lamarkiana	1	2	1	2	1	1		2	1						2				1								2						1
Quinqueloculina parkeri																																	
Quinqueloculina sp.																1			1				1		1							1	1
Sorites orbiculus	1		1		2		1		2	1		2	3		2	2	1	3	2	1	3	2		1	3			1	2		1	4	1
Soritinae	1																																
Spiroloculina sp.	1			1	2	3	3		2	1			2	2	1	2			2		1	3	2	2	2		1		2		1		1
Spirosigmoilina sp.																																	
Triloculina sp.																																	
Vertebralina sp.																																	
Miliolida			1		1					3	1	1	1							1								2		1			4
Cylindroclavulina sp.																																	
Reophax ? sp.					1																1												2
Siphoniferoides siphonifera	6	12	16	12	11	10	5	5	9	7	12	16	11	9	8	17	13	3	11	11	11	8	7	9	10	7	9	13	5	15	12	10	18
Textularia agglutinans			1	1	1	1	1	1			2	1	1	2		3		2	2	3	1	2	1			2			1	2	2	4	
Textularia crenata	1	1	1	3	4	3		2	2	3	3	4	3	2	6	2	2	3	2	5	2	5	1	2	2	8	2	3	4	3	3	3	3
Textularia dupla	2	2	1		2		2		3	4		1	3	1	4	3			5	3	1	2	5	4	4	2	3		1	2	6	2	6
Textularia foliacea	1	2	1		1			2	2	1	1	2	1	1	4	2	1						2		3		2	2	1	1	1		1
Textulariida									1		2	2		1	1		2						1		1	1	2		1		1	1	
Acervulilnidae	1		1			1						2	1					1		1			2	1		1							
Globigerinida	1							1							1	3	1	3			4							3		3			
Spirillina ? sp.													1								1												
unidentified	1	1	1							2	1		1				1	2	2	2	1			1		1	1		1	2	1		1
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1	1	1	1	2	1	2	1	3	1	3				2		1	3	3	1		1	1	1	2	3	2		1	2	2	1		3	1	1		4	1	2
1			2		1			1	2						2		1		2	1	2	1	1	2	1	1	2				1	1	2		2			1	2
14	7	5	12	15	13	13	19	19	11	14	18	21	17	8	11	14	8	20	11	13	14	10	9	3	13	10	7	16	9	13	9	7	10	7	10	11	14	12	11
1		1		1	3			1	1	2	4	3	2	2	3	1	1	1	1		1			1		2	1	2	1		1	1			2	1			
5	3		4	3	4	3	5	4	3	7	6	6		6	3	6	4	2	1	5	5	2	5	5	2	2	1	4	4	1	2	2	1	1	4	4			2
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1		3	4	2		6	3	3	1	4	2		2	3	2	1		2	3	1	4	2		1	2	3	2	2	6	3	3	1	3	3	3	2		2	3
	1		1			1	7				1		1		1			2	1			2	1		1	3	2			1	1	1	2	1	2	1		2	2
			1	2	2	2	2	2						1	2	5		1	2	1	2			1	4	1	1	3		2	2	5	4	5	5	3	1	5	1
			2			1				3				1	2							1	1				1	1	1		1					1	1	2	1
			1												1										1			1		1					1				
1		1	2	2	2	1	2	2	1	3	4	1		2		1	2		2		2	1				1	2		1		3			1		2	1		
153	112	72	129	113	136	145	218	139	112	169	164	162	123	142	126	105	130	128	129	121	138	149	101	106	108	105	150	164	162	124	122	143	122	95	117	149	135	164	191

74	75	76	77	78	79	80
73-74	74-75	75-76	76-77	77-78	78-79	79-80
12	9	15	13	17	21	12
1		1		1		
1						
2			1	1		
1				1		
1		1		1		
			1			1
1				1		2
		1	1	1	1	1
			1		1	
	1					
2	6	3	11	8	9	5
	1					
				1		
2	1	3	4	1	1	2
5	1	5	5	7	2	13
8	6	11	11	5	6	17
				1		
2						
	1		1	1		1
1						
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1		2	2		2	2
3	3	3	4	1	4	2
1					1	1
		1	1			
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2	2	4	5	4	3	3
1						
			1		2	1
	1					

1			1			
5	7	5	7	3	5	11
		1	1			
	1					
						1
2			1			2
5	5	8	9	8	8	9
			2		1	1
		3	2			
1		1	1	1		2
2		1		1	1	
1	2	1			1	
			2			
	1		3		1	1
64	48	71	91	66	73	94

154	155	156	157	158	159	160
153-154	154-155	155-156	156-157	157-158	158-159	159-160
15	9	12	17	21	11	13
1			1			
2	1	1	1		1	
		1	1	1		
1			1	2		
		1		1	2	
3	2			2	1	5
						1
	1					
8	3	7	6	6	4	3
					1	1
		1		1		
	3	1	1	5	2	2
5	6	10	7	5	7	3
	1					
20	15	15	17	6	10	17
2		4				
	1	1	1	2	1	

			1			
1	2					2
		1				
3	3	3	1	2	6	2
6	8	2	5	2	3	5
	1				1	
						1
3		1	3	1	1	
4	3	3	1	1	1	4
		1	1	2	1	1
					1	
		1				
		1	1			
2	4	1	4	1		1
	2			1		
		1			2	1
3			1			
7	8	10	7	10	5	12
	3		1	2		
2		3	2	2	3	
	3	2		2	2	
	1		1	1		
3	2	1				
	1	1	1	1		
1		2				
1			2			1

93	83	88	85	80	66	75