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REPORT

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# Larger foraminifera and sedimentation around Fongafale Island, Funafuti Atoll, Tuvalu

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**Abstract** Larger foraminifera are an important component of coastal sediments around Fongafale Island, Funafuti Atoll, Tuvalu, and at least 10 species are present. In the shallow lagoon, foraminifera (mainly *Amphistegina lessonii*, *A. lobifera*, *Baculogypsina sphaerulata*, *Calcarina spengleri*, *Marginopora vertebralis*, and *Sorites marginalis*) are the dominant component of sand and gravel, followed in decreasing order of abundance by calcareous red and green algae, coral, and molluscs. In deeper water, *Halimeda* replaces the foraminifera. Close inshore, abrasion removes *Halimeda* and may reduce the number of foraminiferal tests. There is some sediment movement in both onshore and offshore directions although offshore transport appears minor. On land, dissolution that preferentially removes aragonite may increase the proportion of foraminiferal tests to as much as 83% of the subsurface sediment. Sediments on the ocean side are dominated by coral and coralline red algal debris thrown up in 1972 by cyclone Bebe and later moved inshore and lagoonward.

**Keywords** Carbonate sediments · Fongafale Island · Funafuti Atoll · Larger foraminifera · Sedimentation · Tuvalu

## Introduction

Foraminifera are an important component of Pacific marine ecosystems, although as yet they are generally poorly understood for this region (Murray 1991). The taxonomy of some groups, particularly the miliolids which show variable morphology, also requires considerable study. Many species are potentially useful as sediment tracers, as indicators of environmental stress, and as producers of carbonate sediments (the "larger foraminifera") (Cockey et al. 1996; Hallock 2000; Woodroffe and Morrison 2001). "Larger foraminifera" is a term used informally and without taxonomic significance for large tropical specimens (up to several cm in diameter) that are common in shallow, oligotrophic tropical seas and may host intracellular endosymbiotic algae. Many are epiphytic and live attached to the substrate or to algae in shallow water on the reef flat. They are particularly important to carbonate sediment budgets because of their size, moderate rates of carbonate production, and resistance to both abrasion and dissolution (Kotler et al. 1992). Tests discarded by foraminifera contribute much of the sand that makes up the land areas of atolls and can be used to trace the movement of sediments (Woodroffe and Morrison 2001).

The distribution and thickness of sediments around Fongafale Island have been the subject of a number of studies because of their importance as sand and gravel resources, their relationship to coastal erosion, and their possible use in infilling the extensive borrow pits on the island (Radke 1985; Smith et al. 1994; Smith 1995a, 1995b; Chunting and Malologa 1995). However, there has been little investigation of the sediment composition or of the foraminiferal faunas since the pioneering studies (Chapman 1900, 1901, 1902, 1910) that resulted from the 1896–98 Royal Society of London Expeditions to Funafuti to test Darwin's theory of atoll formation. This paper presents information on the distribution and significance of the larger foraminifera of Fongafale Island that has come from study of the coastal and nearshore sediments and processes of Funafuti Atoll, Tuvalu. These organisms give information relevant to sediment composition and movement, and can be used to interpret coastal processes. Other details of the sedimentary geology will be presented elsewhere.

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## Methods

### Setting

Funafuti Atoll is located in the south-central Tuvalu Group, western central Pacific Ocean, at 8°30’S latitude and 179°12’E longitude (Fig. 1). It consists of some 39 small islets surrounding a ca. 200 $km^2$ lagoon that is up to 55 m deep (Smith and Woodward 1992). Most of the lagoon floor lies between 20 and 40 m in depth, with the deeper reef channels and most lagoon/ocean water circulation occurring at the western side. The present study utilized material collected on and around Fongafale, the main islet at the eastern side of the atoll (Fig. 1).

These samples are medium to coarse and generally moderately sorted calcareous sands from the shallow lagoon reef flat off Fongafale Island or from channels penetrating it, from the lagoon and ocean beaches, and from the island subsurface. The reef flat here is a broad shelf up to 300 m wide with patch reefs and coral pinnacles which narrows to north and south. Eight dredged subtidal channels cross the lagoon reef flat near Vaiaku (Fig. 1), all apparently excavated between 1943 and 1945 and which have directed sand offshore from the reef flat system (Radke 1985). These extensive modifications of the lagoon side of the island during World War II included a 2.3-km-long reclamation of reef flat along the lagoon side of the central Fongafale with a coral rock seawall, a long borrow pit (often called a channel) beside

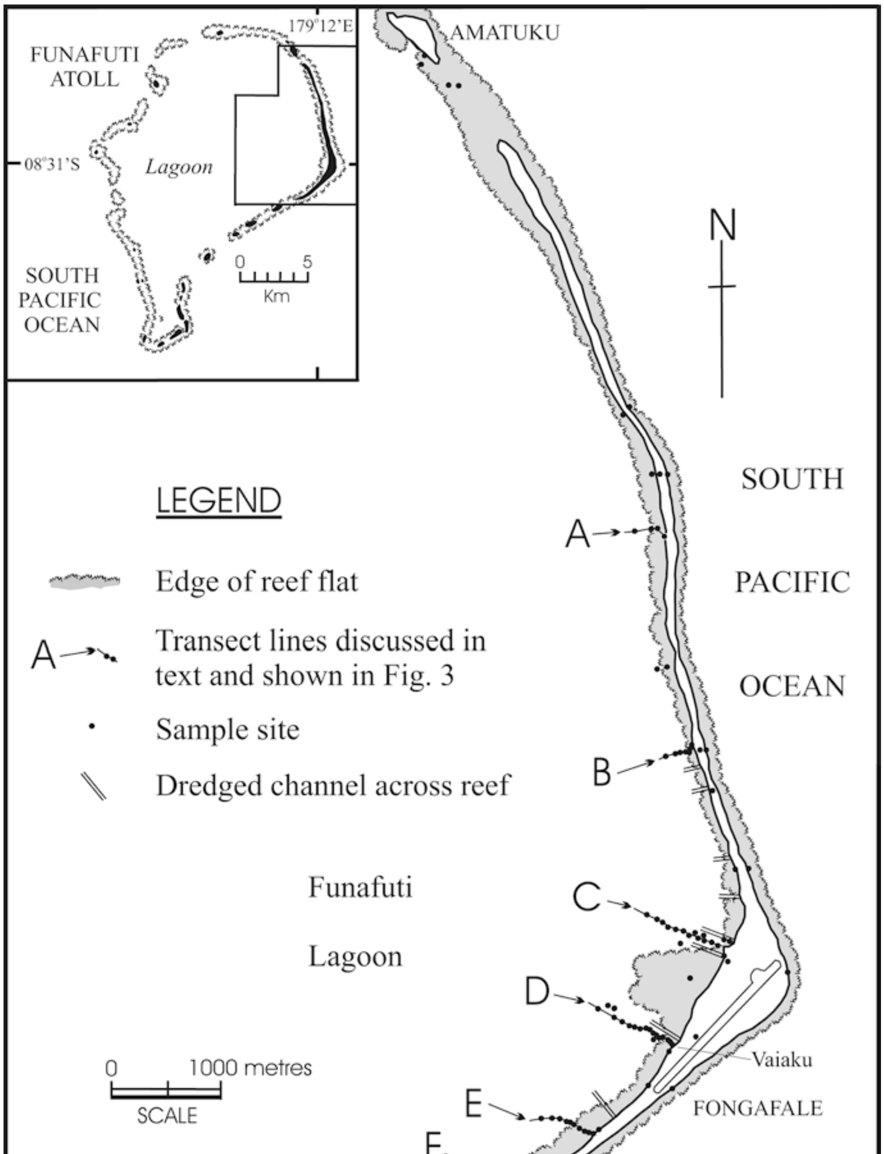


**Fig. 1** Locality map. *A* Inset of Funafuti Atoll showing position of Fongafale Island on eastern side of lagoon. *B* Fongafale Island and adjacent reef flats, showing locations of sample transects discussed in the text, other significant sampling sites, and channels dredged across the lagoon reef flat. Other apparently artificial channels run parallel to the shore between transect lines *C*, *D*, and *E* (not shown on map)

it, and other channels normal or parallel to the seashore on the lagoon side. All appear to have affected coastal processes considerably.

Winds are dominantly from the east to southeast (Carter 1986; Smith 1995b) and produce weak currents in the lagoon off Fongafale, although water circulation here is generally poor. Limited temperature data for the area (Smith 1995a) show stable values averaging 29.8 °C at 15-m water depth.

## Samples and methods

*Samples:* The present study utilized material collected from the shallow lagoon, reef flats, beaches, and land deposits of Fongafale Island (Fig. 1). The sample suite available comprised 85 sediment samples collected in 1984 as part of a bathymetric and coastal resources survey (Radke 1985) and a further 125 samples collected by the senior author in 1995 and 1996 as part of a study of the foraminifera of Funafuti.

Ninety-three samples for detailed study were selected along seven transects aligned normal to the lagoon beach (Fig. 1), with other samples selected from beaches, ocean reef flats, and the shallow lagoon in order to provide sufficient material to overcome the effects of local facies variations. A few samples from trenches and borrow pits on land were selected to complete the traverses, where it appeared that the in situ sediment had not been disturbed by human activities.

*Component analysis*: Samples were sieved and grains from the 0.25, 0.50, 1.00, and 2.00 mm and coarser (2.0$\varphi$, 1.0$\varphi$, 0.0$\varphi$, $-1.0\varphi$, and $>-1.0\varphi$) size fractions were identified to one of 29 categories and counted under a binocular microscope (Table 1). A minimum of 300 grains per size fraction was counted, except where insufficient material was available (mainly in some of the coarse size fractions). The overall composition of each sample was calculated using the composition of each fraction multiplied by the proportion of that fraction of the total sample weight. The $<0.25$-mm fractions (usually very minor) are here assumed to have the same origin as the remainder of the sample. Average results for 93 samples are given in Table 1 and the overall average composition (Fig. 2A) is the result of more than 100,000 clast identifications.

Since distinction between the different species of *Amphistegina* can often not be made from small fragments, clasts were initially identified to generic level and the proportions of *A. lessonii* and *A. lobifera* were then

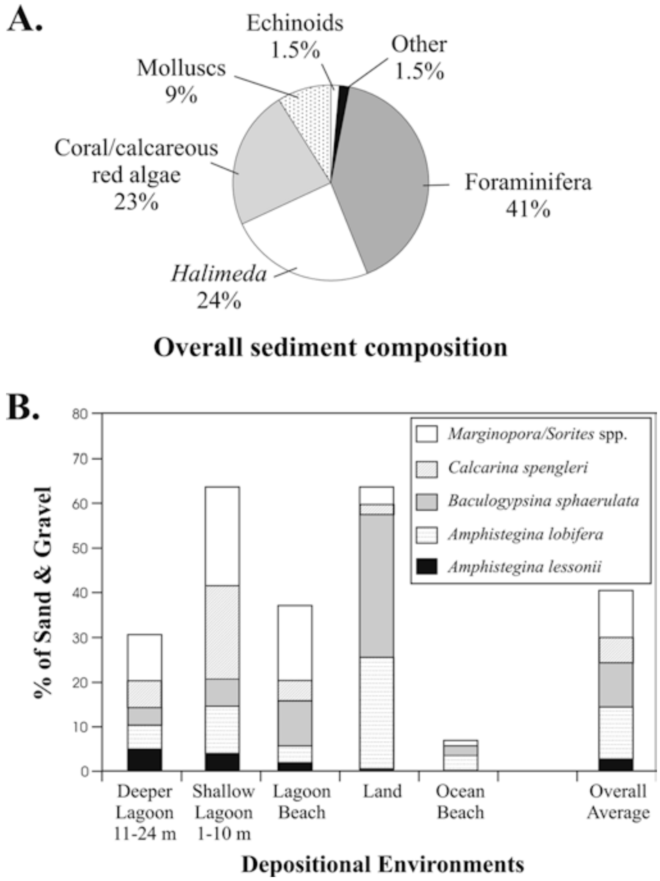


**Fig. 2 A** Pie diagram showing average sediment composition for 93 samples from all the above depositional settings. **B** Average proportions of the main species of larger foraminifera shown as percentages of the total sediment, for samples from different settings

**Table 1** Average percentage compositions of foraminiferan assemblages for 93 sediment samples from various depositional settings around Fongafale Island, Funafuti Atoll

| | Deeper lagoon 11–24 m | Shallow lagoon 1–10 m | Lagoon Beach | Ocean Beach | Land | Overall average |
|---|---|---|---|---|---|---|
| *Amphistegina lessonii* | 5.7 | 3.8 | 1.3 | 0.0 | 0.4 | 3.0 |
| *Amphistegina lobifera* | 4.5 | 10.9 | 14.8 | 3.1 | 24.9 | 11.9 |
| *Baculogypsina sphaerulata* | 4.0 | 6.6 | 10.2 | 2.2 | 31.7 | 9.3 |
| *Calcarina spengleri* | 6.2 | 8.0 | 2.7 | 0.0 | 2.3 | 5.7 |
| *Marginopora/Sorites* spp. | 10.0 | 12.4 | 8.6 | 0.8 | 11.1 | 10.2 |
| Other larger foraminifera | 0.7 | 0.4 | 0.1 | 0.0 | 0.1 | 0.3 |
| Textulariids | 1.0 | 0.3 | 0.1 | 0.0 | 0.0 | 0.3 |
| Smaller miliolids | 0.7 | 0.4 | 0.1 | 0.1 | 0.1 | 0.3 |
| Smaller rotaliine forms | 1.3 | 0.8 | 0.3 | 0.0 | 0.1 | 0.7 |
| Total foraminifera | 34.1 | 43.5 | 38.0 | 6.1 | 70.7 | 41.7 |
| Other clasts | 65.9 | 56.5 | 62.0 | 93.9 | 29.3 | 58.3 |
| Number of samples *n* | 14 | 49 | 13 | 10 | 10 | |

estimated by extrapolation from counts within the 0.5–1.0 mm fraction of each sample. Similarly, because it is often difficult to reliably distinguish calcareous red algal from coral fragments without detailed point counting of thin sections, they are combined in the present report.

## Results

### Distribution of larger foraminifera

Ten species of larger foraminifera have been identified from Funafuti sediments. Those most important to sediment production are *Amphistegina lessonii*, *A. lobifera*, *Baculogypsina sphaerulata*, *Calcarina spengleri*, *Marginopora vertebralis*, and *Sorites marginalis*. To facilitate counting and because they have similar hydraulic and other properties, *Marginopora* and *Sorites* have been treated together here. Also present but usually in small numbers and hence not significant contributors to the sediments are *Anomalinella rostrata*, *Borelis melo*, *Heterostegina depressa*, and *Peneroplis pertusus*. A diverse fauna of other foraminifers dominated by smaller miliolids also occurs (Collen 1998); these are not discussed further here.

The distribution of the dominant larger species along the shallow lagoon transects is shown in Figs. 3 and 4. Figure 3 shows the foraminiferan abundances as a percentage of the total sediment along the transects. The

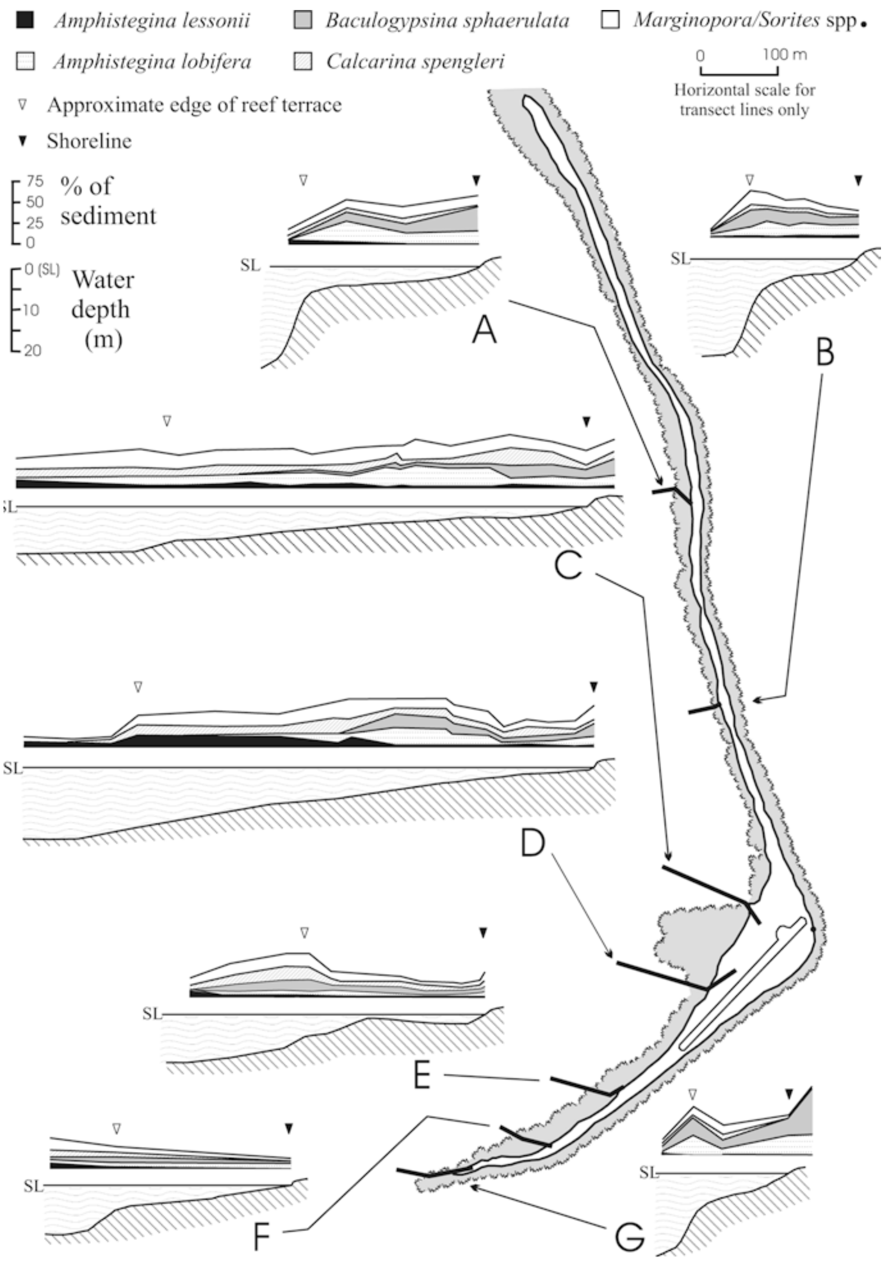


**Fig. 3** Relative abundances of most common larger foraminifera shown as a proportion of total sediment along sample transects shown together with water depths along transects

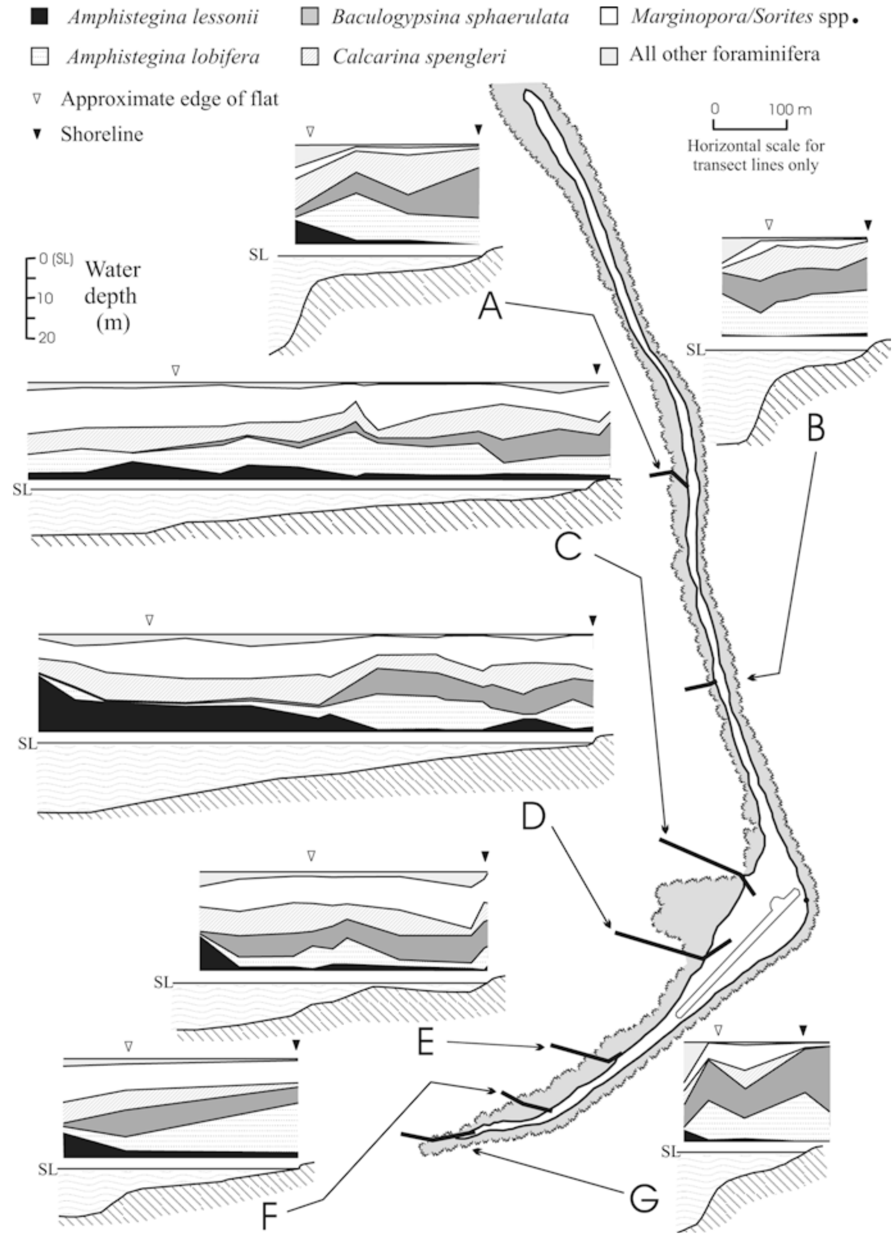


**Fig. 4** Relative abundances of most common larger foraminifera along the sample transects of Fig. 3

quantitative data show that, overall and in some specific environments, the larger foraminifera listed above are the dominant component of the sediment (Figs. 2 and 3). Despite their diversity and abundance, the remaining, generally smaller foraminifera make only a minor contribution (Table 1). The average composition of sediment in samples from the shallow water, beaches, and land of Fongafale is 41% foraminifera, 24% *Halimeda*, 23% coral and calcareous red algal debris, 9% molluscs, and 3% other organisms (Fig. 2A). For medium sand to gravel from specific environments, the foraminifera comprise on average 44% of the shallow lagoon sediments, 38% of the lagoon beach sands, 6% of the ocean beach sands (due to the coral debris provided by tropical cyclone Bebe in 1972), and 70% of the island sands (Fig. 2B).

The foraminiferan data replotted as the relative abundances of the common species along the transects (Fig. 4) shows that, even though most faunas are a mixture of in situ and transported tests, the samples indicate a consistent zonation with respect to distance from shore. Of the two species of *Amphistegina* present, *A. lessonii* is more abundant on the outer part of the lagoon reef flat and into the deeper lagoon and *A. lobifera* is most abundant on the middle and inner parts of the lagoon reef flat. The latter genus also occurs on the ocean reef flat and is very abundant in the land deposits. *Baculogypsina sphaerulata* is most abundant on the middle and inner parts of the lagoon reef flat, is very abundant in the land deposits, and is occasionally found on the ocean reef flat. The large discoidal *Marginopora vertebralis* and *Sorites marginalis* are present in reasonable numbers across the lagoon reef flat but are slightly more abundant towards the deeper part. They are not usually common in the land deposits except occasionally in the coarser material, and have not yet been found on the ocean reef flats where recolonization by foraminifera still occurs (Collen 1996). They may form surface drifts on the beaches in some areas (for example, along the northern lagoon coast of Fongafale), since they are easily segregated and moved by waves because of their relatively low settling velocity in water (Maiklem 1968). *Calcarina spengleri* has a similar distribution, being most common towards the outer lagoon reef flat, but has not yet been found on the ocean reef flat.

Individuals of all species have been found over the range of lagoon depths sampled (Figs. 3, 4). This is partly due to overlapping depth ranges and partly to mixing during transport. Overall, though, the depth distribution of larger foraminifera in the shallower lagoon samples determined from the compositional counts shows that *Amphistegina lessonii* is most abundant in water deeper than 10 m. *Marginopora*/*Sorites*, *Calcarina,* and *Baculogypsina* occur together most commonly in water shallower than this over the outer two thirds of the reef flat, and *Amphistegina lobifera* is most abundant in water shallower than 5 m. Where the reef flat is very narrow with a steep dropoff (e.g., Fig. 3, transects B and G), all species are found together on the outer part of the reef flat.

The sediment composition varies for the different nearshore environments. Figures 5 and 6 show the sample compositions plotted on a ternary chart for the major component groups.

Lagoon sediments are mainly composed of *Halimeda* fragments and foraminiferan tests. In general, the proportion of *Halimeda* increases in the deeper water samples, and sediments of the central lagoon (not sampled here) are dominated by *Halimeda* plates (Chapman 1901; David and Sweet 1904; Smith 1995b).

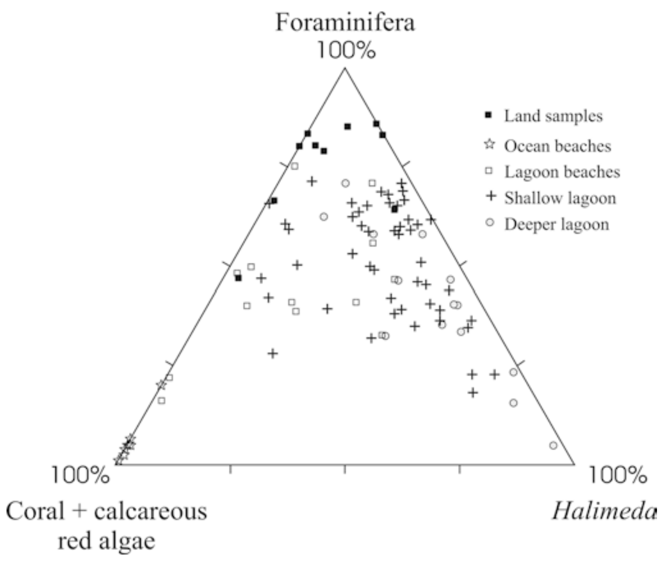


**Fig. 5** Ternary diagram showing relative proportions of coral/calcareous red algae, foraminifera, and *Halimeda* spp. in the samples examined

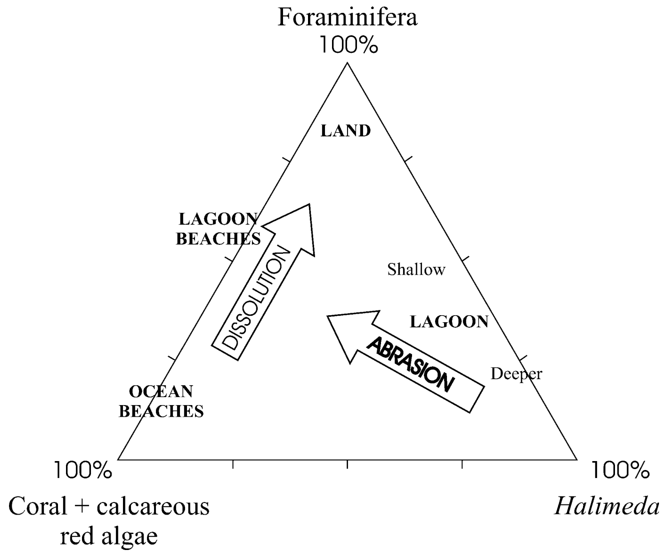


**Fig. 6** Depositional environments for samples plotted in Fig. 4, and representation of trends in compositional change suggested resulting from abrasion and dissolution

Lagoon beach sediments are dominated by foraminiferan tests and coral/calcareous red algal debris. The foraminifera generally increase slightly in abundance onto the lagoon beaches compared to the inshore area. Tests are often polished and abraded, and the spines of *Calcarina* and *Baculogypsina* are usually damaged or missing. The main foraminiferan species occurring in the lagoon beach deposits are *Amphistegina lobifera* and *Baculogypsina*, but *Marginopora* and *Sorites* may be locally common.

Ocean reef flat and ocean beach sediments are almost entirely coral and calcareous red algal debris with a small foraminiferal component (maximum of 20% but normally less than 7%; Fig. 7). The coral and algal material is largely debris derived from the coral rampart deposited on the ocean reef flat by cyclone Bebe in 1972 (Maragos et al. 1973; see below). Concentrations of foraminiferan tests are sporadic on the beaches and consist mainly of *Baculogypsina* with lesser numbers of *Amphistegina lessonii*, *A. lobifera*, *Marginopora*, and *Sorites*. *Calcarina* has not been found.

Onshore deposits are dominated by foraminifera (up to 83%, average 71%), especially the tests of *Amphistegina* and *Baculogypsina*. The tests are often infilled with fine material and loosely cemented, with meniscus features apparent.

## Discussion and conclusions

### Larger foraminifera and sedimentation

The larger foraminifera have a mainly epiphytic habit. Around Fongafale, they occur living particularly on the

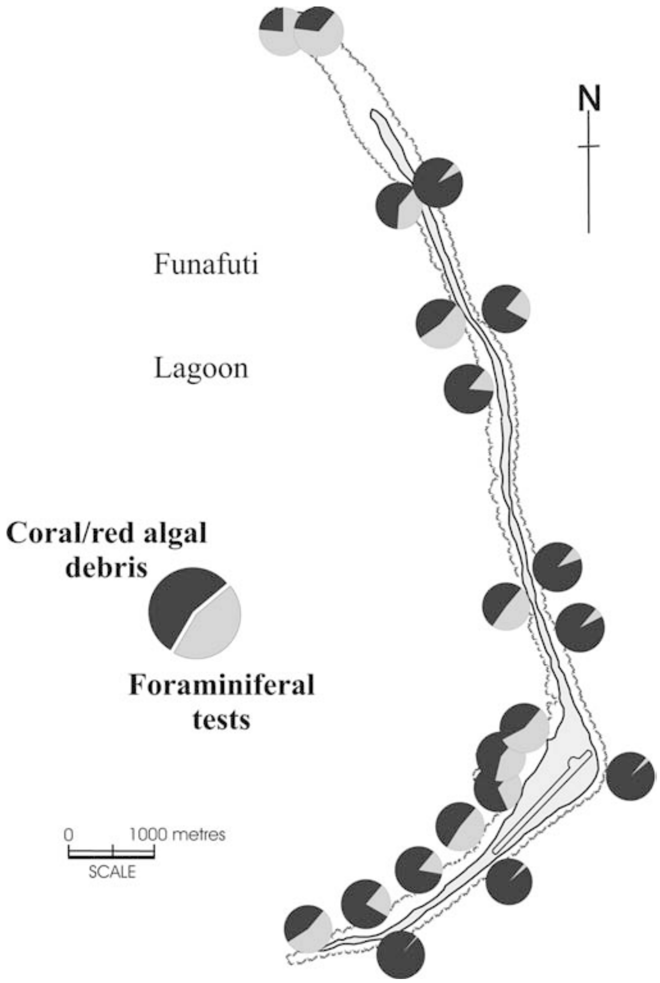


**Fig. 7** Pie charts showing relative proportions of coral and calcareous red algal debris (*dark shading*) and foraminiferan tests (*lighter shading*) in beach deposits around Fongafale Island, Funafuti Atoll

algae *Turbinaria ornata* and *Caulerpa racemosa*, on sea grasses, and on dead coral skeletons. Lack of algal growth and of coral skeletons on the cyclone-smoothed ocean reef flat surface are probably the main factor inhibiting foraminiferan recolonization there.

Foraminifera are most abundant in the outer part of the lagoon reef flat, on some beaches, and in onshore sediments (Fig. 3). The outer lagoon reef flat abundances are most marked where the reef flat is narrow with steep dropoffs (e.g., Fig. 3, transects A, B and G), where peak abundances are reached in water depths of 5 to 15 m. The depth distributions generally agree with those observed for other Pacific lagoons, particularly with respect to the species of *Amphistegina*. The occurrence of *A. lessonii*, with its thinner and flatter test, in deeper waters appears related to light-inhibition of its reproductive processes (Hallock 1979, 1981). In contrast, *A. lobifera* , which is more spherical and requires higher light intensities for reproduction, dominates in shallower waters (usually less than 3 m; Hallock 1981). In Fongafale sediments, the presence of *A. lessonii* tests in beach and land deposits on the one hand, and of *A. lobifera* tests in deeper water on the other (Fig. 2B), indicates some transport of sediment both inshore and offshore. In lagoon sediments, the relative proportions of *A. lessonii* to *A. lobifera* average 1.26:1 deeper than 11 m and 0.34:1 from samples shallower than 11 m. However, a number of the deeper samples are in areas of very steep dropoff where sediment may easily move downslope or are adjacent to pinnacle reefs reaching up to shallower depths and likely to have large living populations of *A. lobifera*. If these are excluded, the ratio of *A. lessonii* to *A. lobifera* in deeper water averages 8.12:1.

These data, together with the evidence for only weak current activity in the lagoon (Smith 1995b), suggest that the main sediment movement is from the shallow lagoon onto the beaches. It is likely that the channels dredged in 1943 initially acted as conduits for sediment movement into deeper water (Radke 1985) and contributed to coastal erosion along the central lagoon coast of Fongafale (Chunting and Malologa 1995). The foraminiferal data discussed above, together with evidence of slow re-establishment of the central Fongafale beaches (Chunting and Malologa 1995), suggests that the nearshore sedimentary system has now stabilized.

The proportion of damaged foraminiferal tests increases shorewards, although some accumulations even on land contain tests in excellent condition. Similar observations were made by David and Sweet (1904) for foraminiferal sediments in the now-infilled mangrove swamp area of central Fongafale. The effects of abrasion incurred during transport include breakage or removal of spines from *Baculogypsina* and *Calcarina*, damage to surface ornamentation and chambers, and polishing of the test surface (especially apparent for *Amphistegina lobifera*). In subsurface samples from onshore, tests show dissolution features that remove the outer test surface and ornamentation, and test infilling with fine material and the presence of meniscus cements are also apparent.

A generalized sequence of events for lagoon sedimentation suggests that sediments are initially formed mainly from *Halimeda*, foraminifera, coral, coralline red algae, and molluscs. As sediment is moved inshore, calcareous algae (especially *Halimeda*) are destroyed by mechanical abrasion in the inner reef flat and beach zone, and the remaining algae plus coral and molluscan fragments are further reduced by freshwater dissolution after incorporation into the island sediment (Fig. 6). The foraminifera are relatively abrasion resistant and have a more stable mineralogy (calcite rather than aragonite) and thus tend to be preferentially concentrated in the subsurface sediments (Figs. 2B, 5, 6).

On the eastward ocean beaches, the sand is composed almost entirely of coral fragments derived from rubble thrown up by tropical cyclone Bebe (Baines and McLean 1976) and a layer of coral blocks overlies much of the surface of the island. However, foraminiferal tests from populations of *Amphistegina lobifera* and *Baculogypsina sphaerulata* recolonizing the ocean reef flat after the scouring effect of the cyclone are increasing in abundance (Collen 1996). Figure 7 shows the relative proportions of coral/calcareous red algal debris versus foraminiferan tests for beach samples around Fongafale Island. Coral and algal debris completely dominates the ocean beach samples and forms a significant proportion of sediments on the lagoon side at the southern end and near the narrowest part of the northern extension of the island, where waves frequently wash across from the ocean side. The coral debris moved inshore after deposition on the outer reef flat (Baines and McLean 1976) and is now reducing in size and moving around the ends of Fongafale and into the lagoon. The southern end of the island prograded by 36 m between 1973 and 1995 (Chunting and Malologa 1995). North of Fongafale Island, where cyclone Bebe did not deposit a coral rampart, sand bar sediments are dominated by foraminifera (Fig. 7) and resemble the subsurface deposits of the main island.

Despite the surficial dominance of coral and algal debris resulting from the cyclone event, compositional data and sedimentological observations from pits suggest that this was a rare event in the development of Fongafale Island. No features resembling cyclone deposits have been observed in borrow pits, where coral blocks are comparatively rare, and it appears that much of the accretion of Fongafale occurred by non-catastrophic processes similar to those forming sandbanks today. We suggest that, barring another cyclonic event similar to Bebe, the oceanside coral debris will be reduced in grain size and redistributed, and sediments with more varied composition will eventuate.

## Changes in sediment composition with time

The existence of sedimentary and faunal information from the 1896–98 Royal Society expedition to Funafuti together with the sample suites collected in 1984 and 1995–96 allows changes in the composition of the nearshore sediments during the 20th century to be examined.

Prior to the 1940s, a broad sandy beach existed along central Fongafale Island (description, photographs, and maps in David and Sweet 1904; Sollas 1904, 1905). This disappeared as a result of the 1943 military construction activities and subsequent erosion (Radke 1985; Chunting and Malologa 1995). No detailed data are available on the pre-1940 composition of the beach sand, although the sands are frequently described as being rich in foraminifera (David and Sweet 1904; Sollas 1905), and it is likely that the proportion of foraminifera was higher than at present.

Similarly, no detailed pre-1940 sediment compositions are available for the inshore part of the reef flat. Foraminiferal assemblages from an east-west traverse collected across Funafuti lagoon and from the surrounding ocean floor in 1898 (David et al. 1904) were briefly described by Chapman (1900, 1901, 1902, 1910). He found greatest abundances and diversity close to the atoll rim on each side, with low abundance and diversity in the center of the lagoon (Chapman 1901). The nearest sample to those examined in the present study is his number 1, collected 800 m offshore in 10 m water depth and approximately equivalent to the deeper samples on transects C and D (Fig. 3). Chapman (1901) recorded 47% foraminifera and 50% *Halimeda* from that site, similar to the present situation.

Comparison of 1984 and 1995–96 samples from similar positions shows that the sediment compositions are generally comparable (Table 2). Larger foraminifera contribute sand-sized grains directly to the sediment at their death or during reproduction, when the empty tests are abandoned, whereas the production of coral and crustose algal debris requires physical destruction or bioerosion of living or dead skeletons. The slight increase over the 11 years in the non-foraminiferal component may indicate continuing re-establishment of equilibrium conditions after the 1943 and later disturbances due to coastal construction and the influence of cyclone Bebe.

It is likely, therefore, that the shallower lagoon sediments were dominated by foraminiferan tests until 1943 and that subsequently habitat degradation and the influx of clasts of coral and algal debris from construction activities diluted their abundance. Living larger foraminifera are abundant on the lagoon reef flats and their production of carbonate is probably again increasing.

The changes in the ocean beach sediments since 1972 were discussed above. Discussion in the reports of the Royal Society expeditions suggests that foraminifera were a minor component of the ocean beach sediments

**Table 2** Average percentage compositions for shallower lagoon samples (< 11 m)

| | Chapman (1901) | This study | |
|---|---|---|---|
| | Sample #1 (~800 m offshore) | 1984 sample suite $n = 21$ | 1995 sample suite $n = 28$ |
| Foraminifera | 47 | 44.9 | 41.7 |
| Halimeda | 50 | 28.5 | 29.1 |
| Coral + crustose algae | 3 | 11.7 | 15.9 |
| Molluscs | | 11.2 | 8.6 |
| Other | | 3.7 | 4.7 |

in 1896–98, although more diverse than at present. Again, the proportion of larger foraminifera appears to be increasing here as the ocean reef flat populations recover.

### Comparison with other atolls

The sedimentary pattern observed around Fongafale Island is broadly similar to that described for a number of other western Pacific atolls (e.g., Woodroffe and Morrison 2001). As examples in very similar settings, larger foraminifera and *Halimeda* are the main contributors to the lagoon sediments of Suwarrow Atoll in the northern Cook group (Tudhope et al. 1985) and Kapingamarangi Atoll in the Caroline Islands (McKee et al. 1959). At both localities, *Amphistegina lobifera* and *Marginopora vertebralis* are the most abundant forms in the shallow lagoon sand sheet where they generally comprise more than 50% (and up to 77%) of the sediment. *Amphistegina lessonii* is the least important species, being most abundant in 10–40 m of water depth and on the tops of lagoon patch reefs. Similar results have also been observed for other atolls of the Tuvalu group, for Majuro Atoll, Marshall Islands, and for Tarawa Atoll, Kiribati (Woodroffe and Morrison 2001, personal observations).

### Proposed dredging for borrow pit infill

An important issue for Tuvalu involves the infilling of the borrow pits excavated on Fongafale Island in 1943 to provide material for military construction. The pits and other low-lying areas have a volume of 785,000 $m^3$ and occupy about 35% (0.5 $km^2$) of the land area of Fongafale Island (Smith 1995b). It has been suggested that an area in the lagoon (close to the ends of transects C and D, Fig. 1) be dredged to provide sediment to infill the pits, and there have been several studies of the feasibility and environmental implications of this (Smith et al. 1994; Smith 1995a, 1995b).

There is concern that the dredging process might lead to increased coastal erosion along the lagoon beaches of Fongafale Island if nearshore sediments move out to fill an offshore excavation. The present study indicates that there is now relatively little movement of sediment from the lagoon reef flat offshore, except perhaps at the southernmost end of Fongafale Island (Fig. 3, transect G) where ocean waves sweep strongly across the narrow reef flat into the lagoon. The evidence presented here suggests that there is relatively little sediment movement into deeper water and it appears unlikely that there would be a major trapping of sediment from the reef terrace in deeper water in an excavation of the modest size proposed. This agrees with a study of the pilot dredging project which showed no significant changes in the seafloor topography (Smith 1995a).

## Conclusions

The quantitative data presented here clearly show the significance of foraminifera to the sand and gravel deposits of Funafuti. In the shallow lagoon (less than 11 m water depth), foraminifera are generally the dominant component of land and nearshore sand and gravel deposits. Most carbonate is being precipitated on the reef flats and the considerable variation in habitats and rapid facies changes mean that large numbers of samples need to be examined in order to obtain representative data for the nearshore area. The preservation of evidence of foraminiferal depth zonation within the sediments suggests that transport is limited, and partly species dependent. However, sediment is moving inshore and accumulating on the beach and land areas. As it moves landward, transport and dissolution processes cause preferential removal of weaker skeletal material (especially *Halimeda*), the dissolution of aragonitic forms (coral, calcareous red algae, molluscs), and hence the concentration of calcitic clasts (foraminifera).

Most larger foraminifera are living in the relatively shallow outer reef flat zone on each side of the atoll. Larger foraminifera as a group are well adapted to warm, shallow, stable oligotrophic conditions and this puts them at a considerable disadvantage when conditions change (Hallock 1985, 2000). They are thus extremely vulnerable to some forms of disruption of the nearshore environment and the major sand-forming foraminifera have in fact disappeared from reef flats adjacent to the densely populated southern islands of Majuro and Tarawa atolls, probably because of increased nutrient levels (personal observations), similar to changes documented in the Florida Keys (Cockey et al. 1996). Such disruptions have the potential to contribute to increased coastal erosion through decreased sediment supply. The larger foraminifera adjacent to Fongafale Island, though, appear to have withstood the changes in turbidity and clastic sedimentation that have occurred during the past 60 years, and there does not appear to have been the increase in lagoon nutrient levels that is seen in other atolls. Presumably the increased turbidity caused by dredging and construction during 1943 and subsequently was of insufficient duration or intensity to have more than a temporary affect. However, the importance of this group to island construction and maintenance over wide areas of the Pacific requires that they be given careful consideration whenever any modification of their habitat is possible.

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