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Research paper

Distribution of large benthic foraminifers around a populated reef island: Fongafale Island, Funafuti Atoll, Tuvalu

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ABSTRACT

Low-lying, small reef islands on Pacific atolls are vulnerable to coastal erosion and flooding, mainly due to rises in sea level, as well as local stresses associated with overpopulation. Because reef island sediments on Pacific atolls are composed mostly of shells of large benthic foraminifers (LBFs), their future stability depends on understanding foraminiferal shell sources and their production rates around the islands. Here, we report on the distribution and population density of LBFs around Fongafale Island, the main populated island of Tuvalu in the South Pacific, where coastal erosion and inundation have occurred. We discuss their controlling factors, in particular, anthropogenic influences on foraminiferal distribution. The results based on multivariate analyses (canonical correlation analysis and multiple regression analysis) demonstrated that *Baculogypsina sphaerulata* and *Amphistegina lobifera* were more common on the high-energy, intertidal ocean reef flats ($\leq 10^6$ and $\leq 10^4$ individuals m^{-2}, respectively), and *B. sphaerulata* was less common around the populated area of the island. On the relatively low-energy subtidal lagoon reef flats, *Amphistegina lessonii* was the most common species, particularly in the dry (leeward) season, with an increasing density in deeper offshore zones ($\leq 10^4$ individuals m^{-2}). *Sorites orbiculus* was less common than the other species, but was found on both sides of the reef flats ($\leq 10^3$ individuals m^{-2}). Macroalgal $\delta^{15}N$ values indicated that upwelling nutrient-rich deep water could be the source of nitrogen for oceanic waters, whereas nutrients in lagoon seawater could be partly derived from groundwater mixing with domestic wastewater, especially near the populated area. These results suggest that the distribution and population density of LBFs in the study area are influenced by spatial differences in water energy and water quality, and that *B. sphaerulata* is less tolerant of nutrient loading than other species. Comparison of distributions between living individuals and empty shells indicated that ocean reef flats are the primary source of foraminiferal shells for reef islands and lagoon beaches.

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1. Introduction

Small, low-lying reef islands with elevations of only a few meters are located around the equatorial Pacific atolls. Sediments underlying these reef islands are composed of unconsolidated bioclasts derived from the skeletons and shells of reef calcifying organisms (e.g.,Chapman, 1902; Cushman et al., 1954; Emery et al., 1954; Hallock, 1981c; Yamano et al., 2005; Perry et al., 2011). These topographical and sedimentological features make reef islands highly vulnerable to increases in sea level and extreme events, such as the erosion of shorelines, flooding of low-lying areas, and saline intrusion into freshwater lenses (Mimura et al., 2007; Woodroffe, 2008). Furthermore, some reef islands have become so urbanized and overpopulated that anthropogenic impacts are now serious issues.

Tuvalu, located near the equatorial South Pacific, is a reef–island nation that is threatened by sea-level rise and overpopulation. It is known as one of the "sinking countries" (Patel, 2006). On Fongafale Island, the capital island of Tuvalu, flooding and inundation occur during spring high tides, known as "King Tides". However, the phenomenon is partly related to increases in the human population and land-use changes since the 1970s (Yamano et al., 2007). Half of the central part of the island was constructed by infilling the original swamp using porous, highly permeable coral blocks (Nakada et al., 2012). Furthermore, 35% of the land area is made up of borrow pits, which were excavated during World War II to provide sedimentary materials for military construction, and in particular for airports (Collen and Garton, 2004).

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Approximately 40% of the land and beach sediments on Fongafale Island are composed of shells of large benthic foraminifers (LBFs), including at least 10 species (Chapman, 1902; Collen and Garton, 2004). However, to date, the distribution and population density of living LBFs have not been studied in detail. Living LBF populations were briefly reported in the 1990s (Collen, 1995, 1996; Collen and Garton, 2004). The ocean reef flats had large living populations of *Baculogypsina sphaerulata*, with lower numbers of *Amphistegina lessonii*, *Amphistegina lobifera*, *Marginopora vertebralis*, and smaller foraminifers. In the lagoon, no living individuals were found close to the shore in populated areas (Collen, 1995). Such knowledge on living LBFs is crucial to fully understand current sources and production rates of foraminiferal shells, and for the future stability of the reef islands in the face of sea-level rise and coastal erosion. LBF production is also of interest for their potential use in restoration, including filling the borrow pits and porous infilled areas.

The distribution and abundance of foraminifers in atoll sediments have been examined at many Pacific atolls (Chapman, 1902; Cushman et al., 1954; Todd, 1961; Tudhope et al., 1985; Ebrahim, 2000; Woodroffe and Morrison, 2001; Bicchi et al., 2002; Yamano et al., 2002; Collen and Garton, 2004). However, detailed distribution and sediment production of living LBFs have been only reported for Majuro Atoll, in the Marshall Islands (Fujita et al., 2009). LBFs such as *Calcarina gaudichaudii* and *A. lobifera* were abundant on turf algae on windward ocean reef flats and in channels between the islands. The population density of LBFs was negatively correlated with human population density. Deterioration of water quality due to sewage discharge and infilling of the channels may have caused the decline of those LBF populations near populated areas (Osawa et al., 2010).

Other foraminiferal studies on the Pacific atolls and islands have also reported declines in LBF populations near populated areas. Hirshfield et al. (1968) first reported the rarity of LBFs in reef flat sediments compared to heterotrophic small foraminifers (miliolids) in the vicinity of a sewage outfall on the populated Eniwetok Atoll island. Ebrahim (2000) reported that living LBFs were absent from lagoons and ocean reef flats near densely populated areas of the South Tarawa Atoll. Carilli and Walsh (2012) reported that the proportion of mixotrophic LBFs in surface sediments decreased significantly over time at all sites on Kiritimati Island, with the largest decreases observed at sites with high fishing pressure. These changes in benthic foraminiferal assemblages on Kiritimati indicate that nutrification has occurred over several decades, possibly due to changes in trophic structure and nutrient cycling caused by fishing.

Water pollution has been reported along the lagoon coasts near the populated area of Fongafale Island, as evidenced by negative redox potentials, high numbers of coliform bacteria and heavy metal contamination in the lagoon water (Fujita et al., 2013, 2014). We hypothesized that the distribution and population densities of living LBFs around Fongafale Island were adversely affected by human activity, as observed in other islands. Here, we report the distribution and population densities of LBFs around Fongafale Island on Funafuti Atoll in Tuvalu, and discuss the controlling factors, with particular attention to the effects of water quality on foraminiferal ecology.

2. Study area

Funafuti Atoll is located in the tropical south Pacific at 8°31′S, 179°13′E, and it is the capital of Tuvalu, consisting of about 40 small islands surrounding a lagoon approximately 50 m deep (Fig. 1A, B). The air temperature is stable throughout the year (28–31 °C). Precipitation is ~3000 mm annually, with higher rainfall from December to March (300–400 mm); however, the difference in precipitation between the dry season from April to September and the rainy season from October to March is small (data from World Weather and Climate Information; http://www.weather-and-climate.com/average-monthly-precipitation-Rainfall,Funafuti,Tuvalu). Southeastern (SE) trade winds are predominant in the dry season, whereas northwestern (NW) winds are predominant in the rainy season. The average water temperature in the lagoon is 29.4 °C with a variation of ± 1 °C throughout the year (air temperature, wind direction, and water temperature data from the South Pacific Sea Level and Climate Monitoring Project; http://www.bom.gov.au/pacificsealevel/index.shtml).

Fongafale Island is located at the southeast edge of Funafuti Atoll, and is bordered by narrow reef flats (Fig. 1C). This capital island has the largest population in Tuvalu, with over 4000 people. This population has increased since the 1970s due to migration and centralization after Tuvalu gained independence, and with the decline in overseas mining operations (Yamano et al., 2007). The populated area is located on the lagoon side of the central part of the island, with residences decreasing toward the northern and southern tips of the island (Fujita et al., 2014). Approximately 70% of the Fongafale population is concentrated in this area (data from Census of Population and Housing and Sample Surveys, 2002, Basic Tables; http://www.spc.int/prism/country/tv/stats/Publication/Pub_index.htm). Half of the central part of the island was originally swamp, which was infilled with porous, highly permeable coral blocks (Yamano et al., 2007; Nakada et al., 2012). Sediments for infilling were excavated from pits, known as borrow pits, on the northern and southern parts of the island (Collen and Garton, 2004). A causeway was constructed by filling inter-reef channels to form a bridge between Fongafale Island and Tengako Island. There is a dumpsite on Tengako Island.

A total of seven line transects were set perpendicular to the shoreline on Tengako and Fongafale Islands (Fig. 1C), and were arranged to capture data from both the populated and unpopulated areas. For each transect, reef flats on both the ocean and lagoon sides of the island were investigated. An ocean reef flat close to the dumpsite in Tengako Island was also investigated.

3. Materials and methods

3.1. Line-transect survey

Line-transect surveys were conducted on reef flats on both the ocean and lagoon sides along three transects (TN, CW, and SM) and at a dumpsite in March 2009. On the basis of results obtained from these transects, an additional four transects (ocean and lagoon sides of L2 , L3, L4 and L5) were surveyed in September 2009. Because shallow-water LBFs are mostly phytal (i.e., attached to algal substrates) and these environments are similar between the dry and rainy seasons, foraminiferal distributions do not differ greatly between seasons. A line transect was set perpendicular to the shoreline using a 100-m measuring tape. The topography was measured using an auto level with a staff. Depth and elevation data were corrected for tidal effects using tide tables for Funafuti obtained from the South Pacific Sea Level and Climate Monitoring Project. The substrata and benthic community were recorded at 10-m intervals to determine ecological zones and their boundaries.

3.2. Sampling

In ecological zones where macroalgae were present, typical macroalgae were collected for foraminiferal analysis. A circular plastic vial (~3 cm diameter) was placed over the algal specimens and the algae were subsequently detached from the substratum by sliding a steel plate under the vial; the vial was then capped with a plastic lid. Four to ten replicate samples were randomly taken from the macroalgae-dominated zone. The samples were immediately fixed with 5% formalin in seawater.

Reef flat water samples were collected to measure nutrient concentrations. Filtered (using a 0.45-μm cellulose acetate filter) surface seawater samples were taken in duplicate from near- and offshore zones along the line transects in March 2009, and again from the near-shore zone in September 2009. The seawater samples were taken during low tide when nutrient concentrations were expected to represent the maximum values due to groundwater discharge and lower mixing

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