Reports

Tropical Cyclone Bebe Creates a New Land Formation on Funafuti Atoll

Abstract. *A huge rubble rampart 18 kilometers long was formed at Funafuti Atoll during tropical cyclone Bebe on 21 October 1972. The material forming the rampart was derived from deeper water offshore. The formation appears to be permanent and indicates that tropical storms may play a significant role in the formation of atoll islets.*

On 21 October 1972, tropical cyclone Bebe struck Funafuti Atoll (8°S, 179°E) from the east before heading south toward Rotuma and Fiji. On Funafuti alone the storm rendered 800 residents homeless, killed six people, destroyed thousands of coconut trees, wrecked four ships, and caused extensive erosion. During the cyclone a huge rubble rampart was formed which was nearly as large as many of the islets, stretching almost continuously for 18 km along the southeastern seaward coast of the atoll. A scientific team investigated the new rampart and other damage at Funafuti between 10 and 24 December 1972. This report describes the rampart, its origin, and its possible fate.

Interviews with residents of the atoll provided considerable information about the storm and its effects. Several hundred photographs were also taken at Funafuti. Scuba divers, using marked transect lines and depth gauges, determined the shallow-water bathymetry of the upper windward reef slope at three locations. Field trips and dives were conducted at most regions of the atoll (Fig. 1). Topographic sections at seven points along the northern half of the new rampart were determined with surveying equipment.

Funafuti Atoll is located in the Ellice Islands which are 600 to 1000 km north of the Fiji Islands. On the night of 20 October 1972, the weather to the northeast of the atoll deteriorated steadily. A barometric depression 70 to 100 km east began heading toward Funafuti. The cyclone intensified rapidly during the afternoon and evening of 21 October. During this time the wind direction gradually shifted from southeast to southwest while the wind speed steadily climbed to velocities in excess of 50 m/sec. Near midnight a 1- to 2-hour lull in the winds indicated that the eye of the storm was passing over the main islet (Funafuti). The lowest barometric pressure associated with the storm (954 mbar) was recorded at the Funafuti Meteorological Station at 2200 hours (1000 hours G.M.T.). After the eye had passed, wind velocities again increased from the southwest and west, and, by midday of 22 October, the cyclone had passed to the south of the atoll.

Sea level began to rise during the early afternoon of 21 October and eventually flooded the airstrip located on the main islet to depths of 1.5 m. The flooding coincided with an expected high tide of 2 m due at 1530 hours, according to astronomical tables. Residents of Funafuti later indicated that at 2215 hours (21 October) a single large wave (the storm surge), possibly followed by one or more smaller waves, swamped the eastern half of Funafuti Island, destroying many buildings and killing several people. The surge was still almost 4 m above the mean high water level after crossing the reef flat and inundating a preexisting high rubble bank stretching continuously along the ocean side of the island. The bank stands about 3 m above the ground level and 4 m above the mean high tide level. The impact of the surge on the bank produced foam and spray up to a height of 15 m. The surge traveled westward across the airstrip to the outskirts of the village area located on the lagoon margin of the island. Damage to the atoll was considerable, especially along southeast-facing shores of islands in the southern half of the atoll. The overall effects of the storm will be reported in more detail elsewhere (*1*).

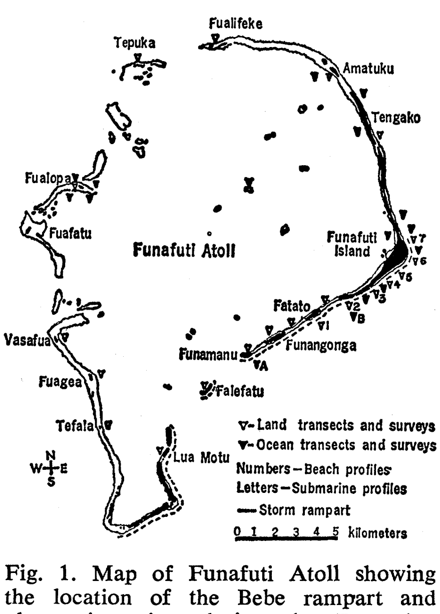

Fig. 1. Map of Funafuti Atoll showing the location of the Bebe rampart and observation sites during the December 1972 study.

The most significant geomorphological effect of the storm was the formation of the nearly continuous rubble rampart on the outer edges of 18 km of the southeastern reef flats. The mean height (above the reef flat) and width of the rampart were 3.5 and 37 m, respectively. The reef flat level roughly corresponds to the mean low tide level. Since the normal tide range is about 1.5 m, much of the rampart is situated well above the intertidal zone. The volume of the new structure is estimated to be 1.4×10^6 m^3 and corresponds to a mass of 2.8×10^6 metric tons. The new Bebe rampart appears recessed behind the outer edge of the reef flat (Fig. 2) and extends along all the shallow reef flats of the southeastern coast but failed to be formed subaerially within the deep passage on either side of Falefatu Island (Fig. 1). There is no consistent correlation between the thickness or shape of the rampart along the coast and the presence or absence of islets. No debris of island origin was seen on the rampart. The structure is commonly one-third to one-half as wide as the islets (Fig. 2). These observations indicate that the rampart material originated from submarine reef slopes offshore.

The mean size (maximum diameters) of surface fragments was about 9 to 10 cm on a representative section of the rampart. The largest storm block observed on the atoll had a maximum dimension of 7 m. Over 99 percent of the mass was composed of particles larger than sand size. Most of the fragments are poorly sorted coral rubble

Fig. 2. Aerial photograph looking north along the southern end of Funafuti Island near land transect 2 (see Fig. 1). This photo was taken at 1000 feet on 10 December 1972. From left to right: Funafuti lagoon; Funafuti Island and damaged groves of coconut trees; the new storm rampart built by cyclone Bebe on 21 October 1972; the breaker zone and edge of the reef flat; and the South Pacific Ocean. Note the anomalies in the new rampart where material appears to have been moved landward. Also note the greater breadth of the rampart at the bottom of the photo.

and shingle (Fig. 3). About 5 percent of the total mass of the new Funafuti rampart was derived from the skeletons of recently living reef corals, most commonly *Acropora*, *Pocillopora*, and *Pavona*.

A moat 2 to 50 m wide separates the storm rampart from the old island shoreline and represents what were formerly the inshore portions of the submerged pre-Bebe reef flat. The water level rises and falls within the moat during tidal fluctuations.

Some modification of the Bebe rampart had occurred during the 6- to 8-week time interval between the storm and our visit to Funafuti Atoll. One or more steep escarpments, probably formed by post-Bebe wave action, appear along all ocean-facing slopes, and the mean size of rubble fragments is locally smaller and more sorted. Sand-sized sediment already predominates along some sections of the base of the ocean-facing slope. At some places the offshore water clarity is reduced by fine calcareous sediments in suspension which may be derived in part from the mechanical erosion of rampart fragments. Residents noted that, within 2 weeks after the storm, wave action had moved the northern end of the rampart in toward the old shoreline. Aerial photographs taken 6 weeks later do not indicate any further modification. Rock fragments are also being toppled landward over the crest of the rampart by wave splash. Backwash may be transporting rubble into deeper water offshore. Low-lying anomalies in the new rampart were seen opposite the southern ends of at least three islets (Fig. 2) and are probably present along other sections of the rampart. Less rubble was initially deposited within the anomalies, and the rampart has been locally pushed up against the old islet shoreline. It is not known whether cyclone activity or poststorm wave activity has caused these features.

Snorkeling and scuba dives were carried out immediately offshore from the rampart (Fig. 1) where the reef slopes presumably received the full force of the cyclone. The upper reef buttresses are moderately steep to depths ranging from 2 to 10 m. In deeper water a broad terrace was commonly found to depths of 20 m. Below the outer edge of the terrace, the reef slope is precipitous to depths of 45 to 65 m. At the bottom are found thick deposits of *Halimeda* sand.

Surprisingly, the shallow-water reef framework appeared undamaged, but the normal reef biota was nearly absent. A few coral colonies of *Pocillopora*, *Acropora*, and *Porites* were still partially alive on the walls of the upper buttresses. Corals, echinoids, and small patches of coralline algae were generally confined to recessed pockets and cracks where the destructive effects of surge and scour would have been significantly reduced. At some sites large blocks appear to have been torn loose from the buttresses and deposited on the rampart. Between depths of 2 and 20 m, a filamentous green alga, *Chlorodesmis*, was found colonizing up to 85 percent of the substrate. Residents of Funafuti indicated that, before cyclone Bebe, the reef slope below 5 m had harbored flourishing coral communities. Evidence of storm damage was notice-

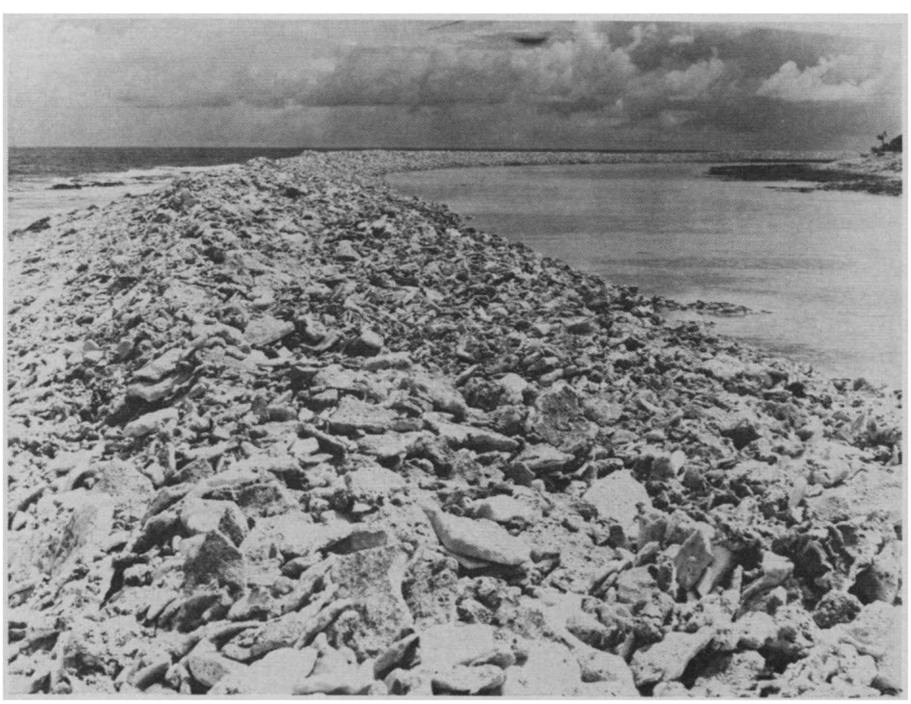

Fig. 3. Waist-level view from the crest of the new rampart facing east. This photo was taken near the site of land transect 7 (see Fig. 1) near the northeastern end of the rampart.

able to depths of 20 to 30 m, below which large populations of fish, corals, and normal benthic algae were locally common although *Chlorodesmis* was absent.

The most significant discovery made during the ocean dives was the presence of large quantities of loose rubble at depths between 2 and 20 m. Much of the rubble is similar in size, shape, and composition to that which comprises the new rampart immediately onshore. A series of dives was also conducted near and past the north end of the new rampart (Fig. 1). Where the rampart was not deposited, normal reef biota was abundant and relatively undamaged. Rubble within the groove and beyond the base of the buttresses was present in sufficient quantity to have formed a rampart. Since the rampart along the northeastern coast was not formed as well as that along the northwestern and southwestern coasts, this suggests that the most powerful wave energy during the cyclone was generated from the southeastern quadrant.

We thus conclude that large waves or the storm surge during cyclone Bebe could have transported rubble material up the slope and deposited it on the reef flat to form the rampart. During movement of rubble, the normal reef biota was killed and this enabled pioneers such as filamentous algae to colonize newly available substrates.

Tropical cyclone Bebe was unusual from several standpoints. It is the only severe storm ever recorded for the month of October since the beginning of written weather observations in the southwestern Pacific. On the basis of accurate historical records, Bebe was only the third severe storm to strike Funafuti Atoll during the past 140 years (*2*). Winds, waves, and surge should reach their greatest development to the left of the center with respect to the direction of movement for cyclones in the Southern Hemisphere (*3*). Observations at Funafuti, which show that the greatest cyclone damage occurred along the southeastern coasts, do not strongly support the theory. For such a small, slow-moving cyclone, Bebe produced a phenomenal storm surge; faster moving typhoons usually produce large surges (*4*). The storm surge height of cyclone Bebe at Funafuti also appears to be much higher than would be predicted by formulas based upon the lowest observed barometric pressures (*5*). On the basis of a review of available weather data, Ramage has concluded that cyclone Bebe approached from the east and then executed a clockwise loop in the vicinity of the southeastern coast of Funafuti Atoll before heading south. Looping seldom occurs over an atoll, and we thus tentatively conclude that the unusual movement of the storm may have contributed to the development of the possible storm surge and to the subsequent damage and deposition at the atoll.

Other studies have shown that the intensity of a tropical cyclone may bear little relation to its depositional effects (*6, 7*). In one study (*8*) it was found that two hurricanes of similar size, which passed over the same region of the Florida Keys within 5 years of each other, effected noticeably different changes. The first storm was largely depositional while the second caused extensive erosion. Factors which determine whether a storm will produce net erosional or net depositional effects include not only the direction of storm movement and the predicted tide level but also the presence or absence of loose rubble deposits at moderately shallow depths.

Although the formation of large rubble banks during tropical storms has been noted in the past (*9*), none has been nearly as large or as extensive as the Bebe rampart at Funafuti. Since no one observed the formation of this rampart, it remains an enigma whether a possible storm surge, storm waves, or both, contributed toward its construction. Although some studies have indicated that storm surges are very destructive events (*10*), these do not always develop during a cyclone. A series of large waves separated by intervals of 20 minutes caused most of the damage at Jaluit Atoll during cyclone Ophelia (*11*).

It appears that the new rampart will be a permanent feature of Funafuti in one form or another. Although wave action may continue to erode and modify the structure, this process may become less effective as the front slope of the rampart becomes more removed from the outer reef edge. Landward movement of rubble bars at Jaluit (*12*) and reef debris in British Honduras (*10*) occurred within 3 years after their deposition by storms. It is assumed that lagoonward movement of the Funafuti rampart will increase the probability of its permanence.

Through one process or another, much of the rampart may eventually be incorporated as atoll land. It is possible that much of the material forming atoll islets may initially have been derived from reef flat deposits formed during storms. Formation of deposits during storms may be normal on Indo-Pacific atolls and also common on Atlantic reefs (*7, 13, 14*). The formation of rubble bars on Jaluit Atoll may occur as frequently as every 30 years (*13*).

Newell and Bloom have concluded that islet formation on Raroia (Tuamotu Islands) has been principally accomplished in the last 800 years during typhoons (*15*). Ball *et al.* have indicated that depositional activity in the Florida Keys by infrequent tropical storms is more important than the sum total of other events (*16*). In the same manner, deposition on Funafuti during cyclone Bebe may also have been much greater than deposition during all other time periods within the last century. Although severe tropical cyclones may be considered to be infrequent phenomena, from a geological time perspective they may play a significant role in the accretion and formation of atoll islets.

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Pressure Dependence of the Radioactive Decay Constant of Beryllium-7

Abstract. *Diamond anvil presses of a new design were used to compress samples of beryllium-7 oxide to 120, 210, and 270 kilobars. The decay constant for the conversion of beryllium-7 to lithium-7 by electron capture was measured for compressed and uncompressed samples. A least-squares fit of the equation* $(\lambda_C - \lambda)/\lambda = K_P P$ *to the experimental data, where* λ_C *and* λ *are the decay constants of the compressed sample and an uncompressed sample, respectively, and* P *is pressure, yields a value of* $(2.2 \pm 0.1) \times 10^{-5}$ *kbar*$^{-1}$ *for the constant* K_P.

Twenty-six years have passed since the independent suggestions of Segrè (*1*) and Daudel (*2*) that the decay constants of certain radioactive nuclides might be altered by varying the electron density in the vicinity of the nucleus. Since that time, several groups have placed nuclides that decay by electron capture and internal conversion in different chemical and physical environments in order to observe these effects (*3*). The two nuclides most frequently used for these studies have been ^{7}Be and ^{99m}Tc.

The first attempts to observe the effect of high pressure on the half-life of a nuclide were carried out by comparing the measured activities before and after compression of a radioactive sample. Bainbridge (*4*) observed that the difference in the decay rate between ^{99m}Tc compressed to 100 kbar and ^{99m}Tc at 1 bar was about 0.02 percent. A few years later Gogarty *et al.* (*5*) used a similar technique to measure the effect of pressure on the decay rates of ^{7}Be and ^{131}Ba. The technique of measuring the effect while the sample remained at a high pressure was used first by Cooper (*6*) on the decay of ^{90m}Nb and again by Mazaki *et al.* (*7*), who repeated the ^{99m}Tc measurement.

The diamond anvil press (*8*) permits studies on small samples at high pressures without the use of large hydraulic devices. We report here results obtained with the diamond anvil press on the change in the decay constant of ^{7}Be in BeO at pressures up to 270 kbar. Beryllium-7 decays to ^{7}Li when a captured electron converts a proton to a neutron.

The values of $\Delta\lambda/\lambda$ measured at 120, 210, and 270 kbar are shown in Fig. 1; the line is a least-squares fit to the equation $(\lambda_C - \lambda)/\lambda = K_P P$, where λ_C and λ are the decay constants of the compressed and uncompressed samples, P is pressure, and K_P is the constant of proportionality. The value obtained for K_P is $(2.2 \pm 0.1) \times 10^{-5}$ kbar^{-1} when P is in units of kilobars. Using the data of Gogarty *et al.* (*5*) for the compression of $^{7}BeCO_3 \cdot Be(OH)_2$ we calculate a K_P value of $(2 \pm 3) \times 10^{-5}$ kbar^{-1}, in agreement with our value of K_P within experimental error. Diffraction patterns produced when an x-ray beam traverses the entire pressure range in a single sample of pure BeO provide evidence that no phase transition occurs. The maximum pressure in this sample calculated from the measured BeO lattice parameters is 300 or 240 kbar, based on the Birch equation with the elastic constants of Anderson *et al.* (*9*) or the shock compression data of Cline and Stephens (*10*), respectively.

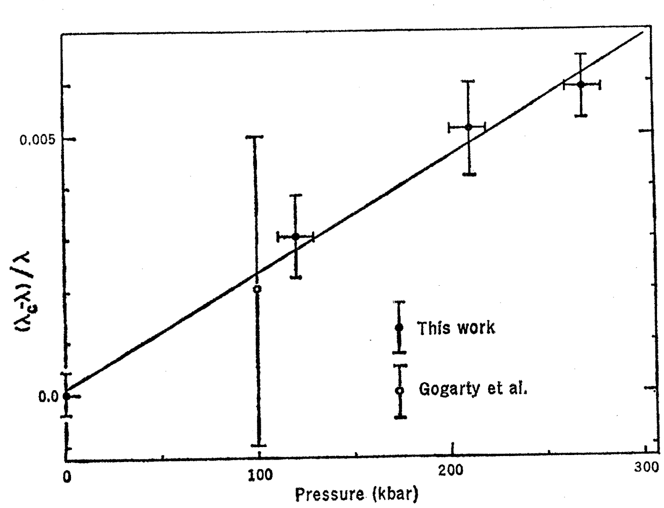

Fig. 1. Fractional increase in the total decay constant of ^{7}Be in ^{7}BeO as a function of pressure; the line is a least-squares fit of our data (see text). Error bars represent one standard deviation. The data point of Gogarty *et al.* (*5*) is calculated from a least-squares fit of 20 measurements near 100 kbar.

The press, which was modified from the one described by Bassett *et al.* (*8*), is a simple piston and screw device constructed from stainless steel. The body of the press is basically cylindrical, 2.5 cm in diameter and 5 cm long. Radiation emitted by the sample emerges through an opening which has a solid angle of approximately 2 steradians. The anvils are 25-mg (1/8 carat) brilliant-cut single crystal diamonds which have had their culet faces enlarged to 0.3 and 0.4 mm.

Samples of BeO were prepared in the conventional radiochemical manner (*11*) from the carrier-free isotope in 0.5*N* HCl (*12*). The pressure samples were made by first compressing a layer of NaCl between the diamond faces. Then the piston with the smaller anvil face was removed from the press and a piece of the ^{7}BeO in the shape of a thin platelet about 0.1 mm in diameter was transferred to the center of the large anvil. The piston was then reinserted into the press, and the press was loaded to its final pressure.

The purpose of including a layer of NaCl between the anvils of the press is twofold. First, it serves as a pressure-transmitting medium, that is, a substance which surrounds and provides a uniform pressure on the entire sample. This results in part from the high compressibility and low shear strength of the NaCl. Second, it serves as an internal pressure standard. Because of the design of the press, it is possible to use standard x-ray diffraction techniques to determine the lattice parameter of