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SEDIMENT PRODUCED FROM ABRASION OF THE BRANCHING STONY CORAL *OCULINA VARICOSA*[1]

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ABSTRACT: Soft rubber tumbling barrels, some with screen windows, were used to simulate natural abrasion of coral branches. Tumbled for equal times, sealed barrels produced more sediment from coral branches than barrels with windows, and dead coral produced more sediment than live coral. Tumbled dead coral produced a gravel mode (2–4 mm) of fragmented barnacles and a sand mode (0.2 mm) of coral. Tumbled live coral produced similar results but lacked barnacles. Time series tests of 1–1000 minutes showed that closed barrels produced increasingly greater percentages of carbonate mud and increasingly finer sand grain-size modes. Tumbling barrels with screen windows yielded particles of unchanging size through the same intervals. Natural sediment with broken coral branches contained coral sand most abundantly between 0.125–0.250 mm, which is the same as produced by tumbling dead coral in barrels with screen windows. Strong grain-size modes at 0.2 mm produced by sonification and tumbling of live and dead coral in sealed and screen-window barrels support the Sorby Principle of skeletal breakdown.

INTRODUCTION

South of Cape Canaveral and along a 110-km segment of the east Florida shelf-slope break at an average depth of 80 m, there are discontinuous ridges, pinnacles, and mounds with relief up to 25 m covered with living and dead *Oculina varicosa* Leseuer 1820, a delicately branching stony coral (Macintyre and Milliman, 1970; Avent et al., 1977; Thompson and Gilliland, 1980; Reed, 1980). Moe (1963) mentioned similar prominences north of Cape Canaveral to Fernandina Beach in northernmost Florida. Our studies of sediments associated with these coral banks show their bulk to be gravel and sand. The gravel consists primarily of broken coral branches, and the sand is a mixture of coral, forams, clams, barnacles, pellets, and quartz. Observations of coral from submersibles (JOHNSON-SEA-LINK, J-S-L I and II) and from time-lapse photography are being used to determine what forces might break the coral. Living *O. varicosa* is white; dead coral becomes bored and encrusted with fouling organisms, which impart a brown surface coloration. Many fragments of coral on the sea floor are white, suggesting that coral breakage is recent and that all broken coral branches are not relict. During one submersible dive, CMH observed finger-size *O. varicosa* branches rolling along the sea floor in a current of 75 cm sec^{-1}. It was apparent that abrasion occurred as the coral branches rolled, and that tumbling barrel experiments might provide useful data on the nature of this abrasion.

The purpose of this paper is to report results of tumbling barrel experiments with *Oculina varicosa*, emphasizing the abrasion products. Although previous tumbling studies have used closed ceramic barrels (Chave, 1960, 1964; Force, 1969), it seems probable that particles abraded from the rolling coral branches physically separate from the branch and settle in other areas. Therefore, tumbling barrels with screen windows were used to permit escape of newly chipped particles, making the tumbling experiments a better simulation of our sea floor observations. Comparisons of sediment from tumbling experiments with natural sea floor sediment show this effort was successful.

METHODS

Living and dead *Oculina varicosa* was collected from 76 m at Jeff's Reef (27°32.8′ N, 79° 58.8′W) and *O. varicosa* rubble from 60 m at one Sebastian Pinnacle (27°44.4′ N, 79°58.8′ W) with a claw and 20 × 20 cm grab

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sampler mounted on the manipulator arm of J-S-L I, dive 1044, 22 June 1981. A technical description and specifications for the submersible is given in Busby Assoc. (1981). Live coral was cleansed of tissue in 5% sodium hypochlorite. Live and dead coral were distinguished by color, and by the presence or absence of fouling organisms and holes made by borers. In this paper, live coral means that no foulers or borers were present. Two- to 8-cm-long branch fragments ($\bar{x}$ length = 4.7 cm, $\bar{x}$ dia. = 0.6 cm) from both live and dead coral were rinsed free of loose sediment, dried, and weighed into test aliquots.

Inspection of dead coral showed that sediment (quartz sand and silt, carbonate fragments) had accumulated in corallites and bore holes. A 14 W cm^{-2} ultrasonic bath was used with the idea of flushing out this sediment, which would mix with particles abraded from the coral, possibly masking or confusing the tumbling results. Coral rested on a rubber mat at the bottom of the ultrasonic tank, which was filled with 1.0 l of tap water.

Soft rubber tumbling barrels, 17 cm inside diameter and 19 cm long with a capacity of 3.8 l, were rotated at 29 rpm. The rubber barrels were molded with 10 flat faces internally, and at 29 rpm, a particle would travel 16 m min^{-1}. The barrel closures were rubber-faced discs. Some experiments used sealed barrels, called *closed-barrel experiments*. Other barrels were modified with two 8 × 1.5 cm slots cut into opposite sides in which stainless steel cloth with 1.0 mm openings was cemented with silicone rubber. The wire cloth was recessed 1.2 cm so that, ordinarily, the coral branches did not contact metal. These barrels were used in open-barrel experiments.

Most barrel charges were 50 g aliquots of coral branches with 1.0 l of tap water in the closed barrels. No sand or pebbles were added to any test; all abrasion was caused by coral against coral. A few experiments used larger coral weights, but all results were normalized to 50 g. The open-barrel experiments were done inside a 190 l plastic garbage can with 30 l of tap water. With the open barrel resting on rollers, water half-filled the barrel. As the barrel revolved, water moved in and out through the wire cloth windows. Particles that escaped through the cloth openings were recovered later by settling.

Abrasion tests were made in two modes, 100 minute runs and time series with intervals of 1, 10, 100, and 1000 minutes; one run was made to 10,000 minutes. Most runs were made with five replicates; figure captions identify single-run experiments. Particles were recovered at the end of each test interval and were not returned to the barrel for successive periods of abrasion. Particles were wet-sieved. Gravel and sand retained on a 63-μm screen was oven-dried at 95° C, dry-sieved on a 63-μm screen, and then weighed. Particles passing the 63-μm dry-sieving were added to suspended silt and clay, which was recovered by settling. Water was removed from the silt and clay through tarred GF/A glass-fiber filters. The filters were oven-dried at 95° C and weighed. Size analysis of the gravel and sand fractions was done by dry-sieving with 7.6-cm stainless steel screens at one-half Phi intervals; screen agitation was by vibrapad. All weighing was done to 0.1 mg. No size analyses were made for the mud fractions.

To determine how the shape of coral branches might change with abrasion, 50 3–8-cm-long pieces of dead coral were measured with a vernier caliper to 0.01 cm, and the long (L), intermediate (I), and short (S) dimensions were recorded. The coral branches were tumbled for 930 minutes in a closed barrel with 1.0 l of tap water. At the end of the run, the coral branches were remeasured and ratios of S/L and L-I/L-S were calculated. Individual and mean ratios for the start and end of this experiment were plotted on Folk's (1968, p. 10) sphericity-form diagram for particle shapes.

As appropriate, homogeneity of variance was determined with the F-max test, and significance of difference ($p < 0.05$) between experimental runs was determined by Student's t-test (Sokal and Rohlf, 1969; Rohlf and Sokal, 1969).

RESULTS

Sonification

It was expected that the amount of sediment produced by sonification would be large at first, and then cease as particles were flushed from corallites and pores. The sonifier did free non-coral contaminants but also acted as an abrader of coral, producing new particles from the coral branches. This occurred for both live and dead coral (Fig. 1). Tumbling experiments with and without prior sonification produced identical

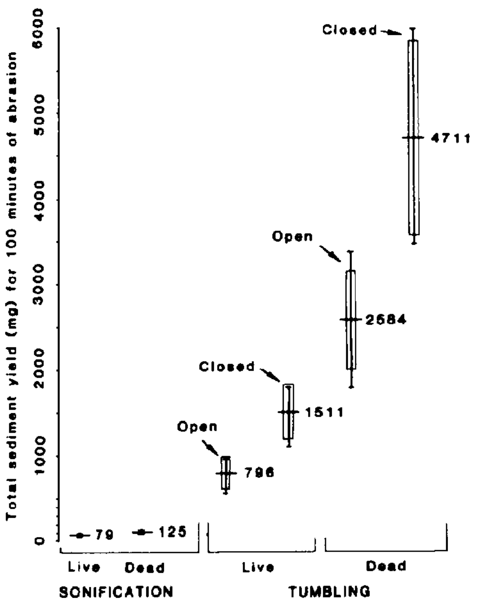


FIG. 1.—Total sediment yield from 100 minutes of abrasion. Horizontal bar and number = x̄ value of 5 replicates, box = ±1 SD, and vertical line = range.

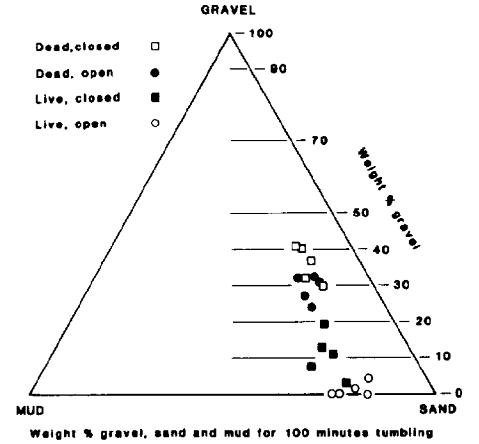


FIG. 2.—Major grain-size classes from 100 minutes of tumbling. Isopleths for sand and mud omitted for clarity.

results. As there is no analog in nature for ultrasonic abrasion, the sonification experiments were helpful only in showing that the amount of contamination from pore-accumulated sediment was not important. Therefore, sonification results will not be addressed further, except for a comment in the Discussion.

100-Minute Runs

The purpose of these experiments was to indicate differences between kinds of abrasion and to set the stage for time-series runs. Figure 1 shows that dead coral yielded approximately twice as much sediment as live coral, and closed barrels twice as much sediment as open barrels. The proportion between major size classes of gravel, sand, and mud are given in Figure 2. Sand was the chief product. Dead coral produced significantly more gravel than live coral, and, for both, closed barrels produced significantly more gravel than open barrels (Fig. 2). Mud production was similar for all runs (12.0–26.7%, x̄ = 17.6%).

Size-frequency curves for the gravel and sand fractions are given in Figure 3. Live coral yielded a sand mode centered on 0.21 mm for both open and closed barrels. In addition, abrasion of live coral in a closed barrel produced a strong gravel mode at 3.4 mm (snapped-off ends of coral branches). There were only hints of this gravel mode in the open-barrel runs for live coral. Tumbled dead coral produced a dominant grain-size mode in the granule gravel range (2.8 mm—open barrel, 2.4 mm—closed

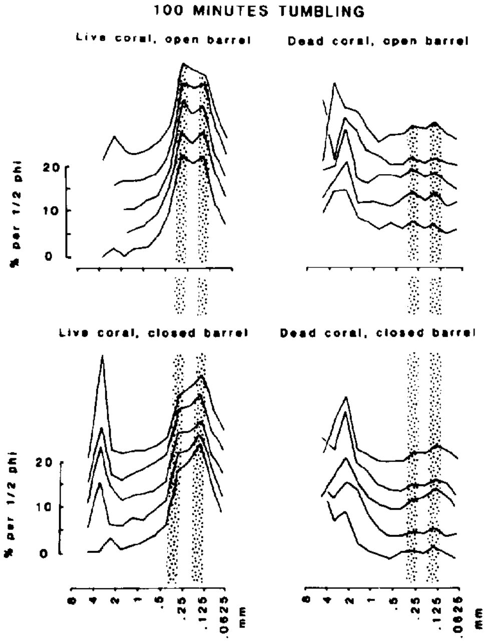


FIG. 3.—Size-frequency curves for sediment produced from 100 minutes of tumbling. Area shaded to compare coral sand grain-size modes. No data for mud-size distribution.

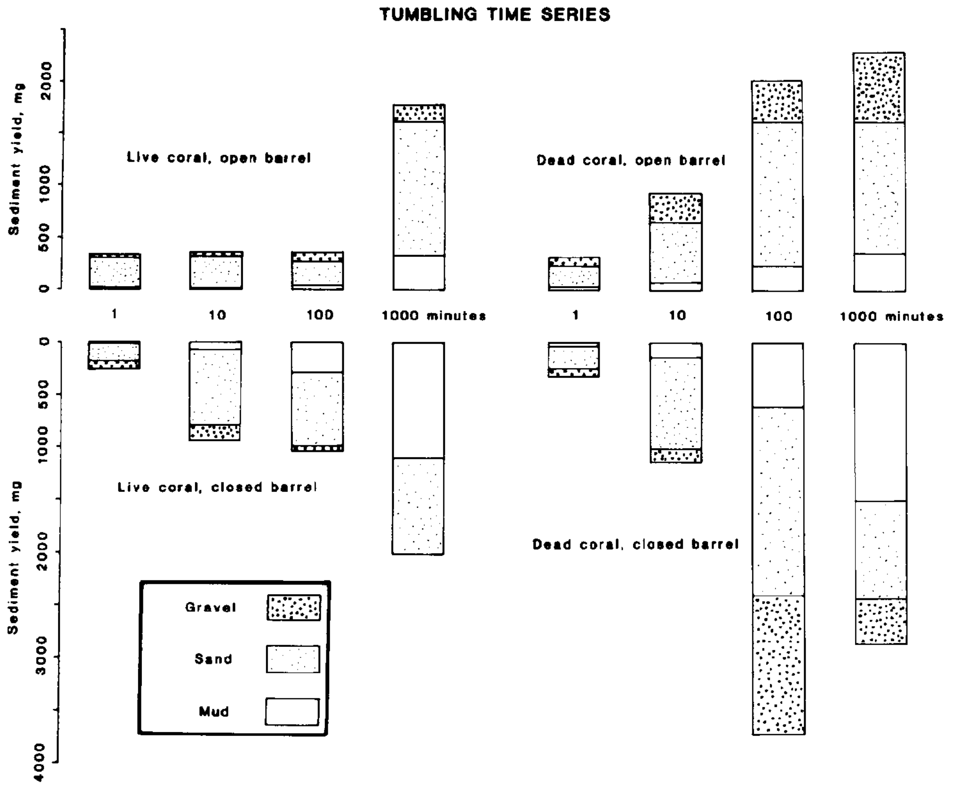


FIG. 4.—Total sediment yield and major grain-size classes resulting from tumbling time series of 1, 10, 100, and 1000 minutes. No replicates.

barrel), consisting of barnacle plates. A coral sand mode was also produced with the peak of its distribution near 0.15 mm.

Time-Series Runs

In the time-series experiments, there was a general increase in the amount of sediment produced as time of abrasion increased except for the dead coral in a closed barrel which produced smaller amounts of sediment after 100 minutes (Fig. 4). Through 100 minutes, closed barrels abraded coral faster than open barrels, but by 1000 minutes this difference had gone. The rate of particle yield was highest during the first minute of abrasion and decreased thereafter for all experiments. The best data set is for dead coral in closed barrels, and mean yield rates were (n = 5) $\bar{x}$ = 323 ± 170; 149 ± 30; 37 ± 3; and 3 ± 0.4 mg min^{-1} for 1, 10, 100, and 1000 minutes, respectively. Other experiments were similar.

In open barrels, the proportions between gravel, sand, and mud for live and dead coral remained relatively constant (Fig. 4). In closed barrels, however, changes did occur for both live and dead coral, with large increases in mud fraction (Figs. 4, 5). The amounts of gravel

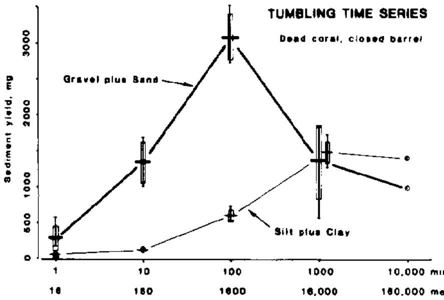


FIG. 5.—Total sediment yield and variations in coarse and fine fractions of sediment for dead coral tumbled in a closed barrel for periods of 1, 10, 100, 1000, and 10,000 minutes. Horizontal bar = $\bar{x}$ of five replicates, box = ±1 SD, vertical line = range, dot = single run.

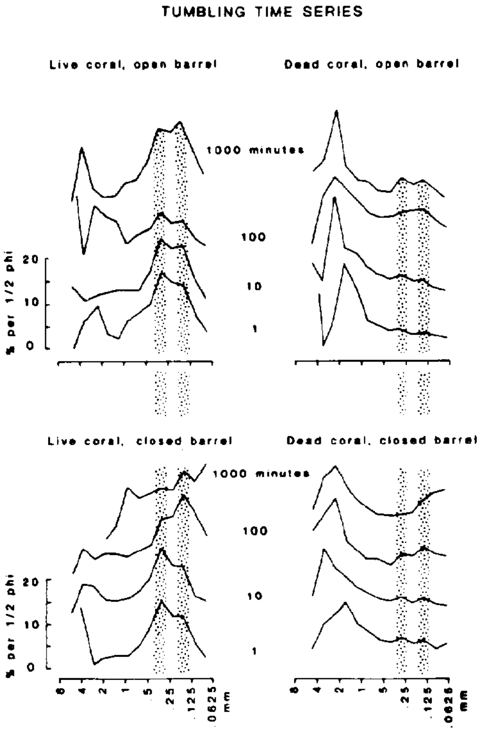


FIG. 6.—Size-frequency curves for sediment produced in time series of 1, 10, 100, and 1000 minutes. All are single runs except for dead coral in closed barrel, which has 5 replicates, and for which the mean curves are given. Area shaded to compare coral sand grain-size modes. No data for mud-size distribution.

plus sand produced increased over the amounts of mud through 100 minutes, after which mud became the dominant fraction.

Tumbling of live coral in an open barrel produced the 0.21 mm sand mode for all time intervals (Fig. 6). Live coral in a closed barrel yielded the 0.21 mm sand mode at 1 minute, which became progressively finer and by 1000 minutes was finer than 0.074 mm. Gravel modes were erratic and many replicates would be needed to discern trends. Tumbling of dead coral in an open barrel produced a strong gravel mode (barnacles) at 2.4 mm, which did not shift with time. The sand mode at 0.21 mm became increasingly more abundant as the time of abrasion increased. Tumbling dead coral in a closed barrel produced a primary gravel mode (barnacles) between 2–4 m, and the 0.21 mm sand mode (coral), which became finer, 0.11 mm by 1000 minutes. This finer-sand mode shifted into the mud range, as judged by two runs of 5340 and 10,000 minutes.

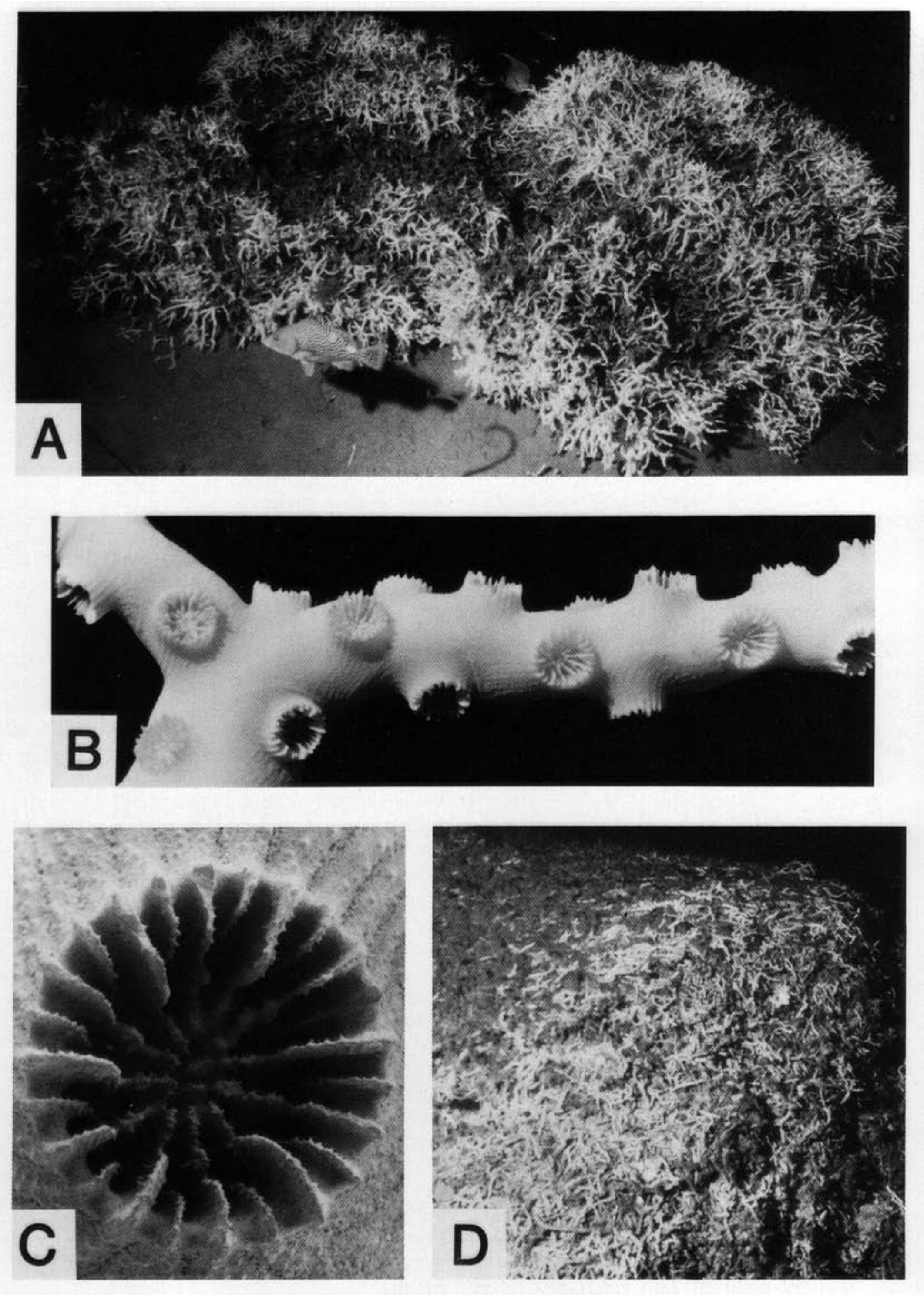
Shape Change of Coral Branches

The average shape change for 50 dead coral branches after 930 minutes of tumbling was a shift from near the elongated pole of Folk's (1968) spericity-form diagram towards the compact pole; S/L (start) $\bar{x}$ = 0.131, (end) $\bar{x}$ = 0.258. There was no change in L-I/L-S = 1. The trend towards a compact form was caused by wear on the coral branch ends. Starting coral weight was 117.32 g for 50 branches, whereas final weight was 99.95 g, consisting of 77 pieces.

DISCUSSION

Most experiments of this study were no longer than 1000 minutes; other workers have used tumbling periods 6–96 times longer (Chave, 1960; Force, 1969). Shorter times were used because peak production of gravel plus sand, and mud, occurred at 100 and 1000 minutes, respectively (Fig. 5). One 10,000-minute run showed a continuation of the trend found at 1000 minutes. Also usable amounts of sediment were produced in the shortest abrasion interval of one minute.

Tumbled for equal times in open or closed barrels, dead coral yielded more sediment than live coral (Fig. 1). This was due both to fragmentation of encrusting organisms (chiefly barnacles) not present on live coral, and to the greater ease of abrasion of dead coral weakened by bioerosion (Chamberlain, 1978). Tumbled for equal times, closed barrels yielded more sediment than open barrels for both live and dead coral (Fig. 1). This is interpreted to mean that tumbling action in closed barrels must be more vigorous. Time-series experiments showed that the proportion of fine particles made in closed barrels increased for both live and dead coral; this did not happen with open tumbling barrels (Figs. 4, 5, 6). For abrasion periods of 10, 100, and 1000 minutes in closed barrels, production of silt plus clay for live and dead coral, respectively, was 8, 28, 55; and 9, 15, 51 wt. % (Fig. 4). Tracking sand grain-size modes through the same abrasional intervals showed that for live coral, the mode shifted from 0.3 to 0.15 to finer than 0.074 mm; dead coral was similar. Shifts did not occur for open barrels.


A
B
C
D

Folk and Robles (1964) called attention to Sorby's much earlier work on skeletal breakdown and cited examples from their own work on *Acropora* and *Halimeda*. Sorby (1879) proposed that the structure of each kind of skeleton influenced the size of its fragments. Some studies on skeleton fragmentation did not find evidence for this (for example Hoskin and Nelson, 1971—barnacles and mollusks; Mitchell-Tapping, 1981—many skeletal types; Force, 1969—mollusks in closed-tumbling barrel). However, data in this report, particularly from the open tumbling barrels (Figs. 3, 6), support Sorby's Principle. These tumbling data and sonification results show that abrasion of *Oculina varicosa* produces particles which are most abundant at 3.4 mm and between 0.15 and 0.30 mm. This strongly suggests that some property of the coral skeleton controls the size of its fragments. Inspection of the coral before and after abrasion shows that the bladelike septa of each corallite were the most severely abraded part of the coral skeleton (Fig. 7). The septa break in elongate wedges (Fig. 7), and the most abundantly produced particles in these abrasion experiments were septal fragments. The greatest width (intermediate dimension) of these septal bits was 0.2 mm for live and dead coral (Figs. 3, 6).

Abrasion in nature also produces the 0.2-mm septal fragments. Samples of sediment from two offshore *Oculina* reefs were sieved and the abundance of coral fragments was estimated with a low-powered microscope through the sand size range at one Phi intervals. At Jeff's Reef, a live coral bank, little coral sand was found although coral branch fragments were present in the sediments. A few miles north in the Sebastian Pinnacles where coral branch rubble is a major sediment type (Thompson and Gilliland, 1980), coral sand was found with maximum abundance between 0.125 and 0.250 mm, just where open tumbling barrel experiments predict it should be. The lack of coral sand at Jeff's Reef may be due to the low current velocity; mean and maximum velocities were determined from a year-long current meter deployment as 8.6 ± 1.7, 58.5 cm sec^{-1} (Reed, 1981, Table 1). In the Sebastian Pinnacles, current meter data are lacking, but instantaneous measurements during submersible dives indicate current velocities commonly of 75 cm sec^{-1}.

These observations show that open tumbling barrels better simulate natural abrasion, and we recommend they be considered in the design of future tumbling experiments. Additional abrasion of coral sand probably occurs in nature, but not to the extent of being ground to mud, as suggested by the closed tumbling-barrel results. Coral branches weakened from bioerosion are subject to breakage when they are rolled by currents, yielding new coral gravel and sand. About 20% of the abrasion products from tumbling experiments is carbonate mud. Mud in natural sediments of these deep-water coral reefs is also formed by bioerosion attack of coral branches, particularly by sipunculids and boring sponges.

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REFERENCES

Avent, R. M., King, M. E., and Gore, R. H., 1977, Topographic and faunal studies of shelf-edge prominences off the central eastern Florida coast: Int. Revue Ges. Hydrobiol., v. 62, p. 185–208.

Busby Associates, 1981, Undersea vehicles directory: Busby Associates, Arlington, VA, 399 p.

Chamberlain, J. A., 1978, Mechanical properties of coral skeleton: compressive strength and its adaptive significance: Paleobiol., v. 4, p. 419–435.

Chave, K. E., 1960, Carbonate skeletons to limestones; problems: Trans. N.Y. Acad. Sci., Ser. II, v. 23, p. 14–24.

Fig 7.—A) Living colonies of *Oculina varicosa* at the base (79 m) of Jeff's Reef. Field of view = 2 m. B) Unabraded branch of *Oculina varicosa*. Length = 4.9 cm. C) Scanning electron micrograph of one *Oculina varicosa* corallite, diameter = 2.8 mm. Width of broken septum (at top) = 0.2 mm. D) *Oculina varicosa* rubble on the crest of one of the Sebastian Pinnacles. Depth = 60 m, field of view = 1 m high.

———, 1964, Skeletal durability and preservation, *in* Imbrie, J., and Newell, N. D., eds., Approaches to paleoecology: New York, John Wiley & Sons, p. 377–387.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, TX, Hemphill's, 170 p.

Folk, R. L., and Robles, R., 1964, Carbonate sands of Isla Perez, Alacran Reef complex, Yucatan: Jour. Geol., v. 72, p. 255–292.

Force, L. M., 1969, Calcium carbonate size distribution on the west Florida shelf and experimental studies on the microarchitextural control of skeletal breakdown: Jour. Sed. Petrology, v. 39, p. 902–934.

Hoskin, C. M., and Nelson, R. V., 1971, Size modes in biogenic carbonate sediment, southeastern Alaska: Jour. Sed. Petrology, v. 41, p. 1026–1037.

Macintyre, I. G., and Millman, J. D., 1970, Physiographic features on the outer shelf and upper slope, Atlantic continental margin, southeastern United States: Geol. Soc. Am. Bull., v. 81, p. 2577–2598.

Mitchell-Tapping, H. J., 1981, Particle breakdown of recent carbonate sediment in coral reefs: Florida Sci., v. 44, p. 21–29.

Moe, M. A., 1963, A survey of offshore fishing in Florida: Florida State Board Cons., Prof. Paper Ser., No. 4, p. 1–115.

Reed, J. K., 1980, Distribution and structure of deep-water *Oculina varicosa* coral reefs off central eastern Florida: Bull. Mar. Sci., v. 30, p. 667–677.

———, 1981, In situ growth rates of the scleractinian coral *Oculina varicosa* occurring with zooxanthellae on 6-m reefs and without on 80-m banks, *in* Gomez, E. D. et al., eds., Proceedings of the 4th Int. Coral Reef Symposium, 18–22 May 1981, Univ. of the Philippines, Diliman, Quezon City, Philippines, v. 2, p. 201–206.

Rohlf, F. J., and Sokal, R. R., 1969, Statistical tables: San Francisco, W. H. Freeman, 253 p.

Sokal, R. R., and Rohlf, F. J., 1969, Biometry: San Francisco, W. H. Freeman, 776 p.

Sorby, H. C., 1879, Anniversary address of the President: Proc. Quart. Geol. Soc. London, v. 35, p. 56–95.

Thompson M. J., and Gilliland, L. E., 1980, Topograhic mapping of shelf-edge prominences off southeastern Florida: SE Geol., v. 21, p. 155–164.