Sedimentation and Coral Reef Development in Turbid Water: Fanning Lagoon[1]

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ABSTRACT: Lack of light and excessive sediment deposition rates are factors limiting coral reef development. The presence of very turbid water and muddy bottom does not mean, however, that coral growth is prohibited. Fanning Lagoon has a turbid water area (visibility, 2 m) and a clear water area (visibility, 10 to 15 m). Both areas have a muddy bottom. Because of the shallow depth and the light-scattering effect of the suspended $CaCO_3$, relative light intensity at the bottom is greater than 5 percent. The cleaning mechanism of the corals is sufficient to handle the deposition of sediment. Live corals cover 62 percent of the clear-water area and 31 percent of the turbid. Reefs in the turbid water are ecologically different from the ones in clear water, but they are still living reefs. Ramose corals make up 55 percent of the individuals in the turbid water and only 10 percent of those in the clear water. This difference is reflected in the structure of the reefs; those in clear water are massive and steep-sided, while those in the turbid water have gentler slopes and are more open with sediment infill. Fanning Lagoon is an example of penecontemporaneous formation of reef and intervening muddy sediment with bathymetric relief never more than 8 m.

THE STATEMENT that coral reefs develop in clear, warm seas is commonly made when dealing with studies of reef growth and development. By induction, reefs therefore do not develop in turbid, warm seas. Stratigraphic analyses of ancient reef complexes are often done using modern coral reef analogues. The idea of clear, warm water is carried into the interpretation as a result of logic. Because of the association between turbid water and deposition of fine-grained sediments, this approach leads to a vision of reefs with tens of meters of relief standing in clear epicontinental seas. Later introduction of fine-grained sediment stunts and kills the reefs and deposits the fine-grained rocks commonly found in the inter-reef areas.

Biological and marine geological literature contains a number of references to survival and growth of corals and coral reefs in trubid water (Crossland, 1928; Kuenen, 1950; Motoda, 1939; Shepard, 1963; Wells, 1957; Yonge, 1930). However, there also are documented cases of reef kill by floods of turbid water associated with periods of extreme freshwater runoff. Decrease in salinity may be the major cause of coral death (Banner, 1968; Goreau, 1964). The range of salinity tolerance of corals is from about 27 to 40 parts per thousand (Wells, 1957). As long as the salinity remains within these limits, freshwater flooding will not seriously affect the coral population as a whole.

The suspended load has two effects. One is blockage of light. When the light intensity falls below some limiting value, many reef-building organisms dies, but only after a period of time. Corals, for example, can live in the dark for some days (Edmondson, 1928). Goreau (1964, p. 384) reported that ". . . 14 weeks after the floods, many of the bleached colonies [bleached due to loss of zooxanthellae] were still much paler than normal although they appeared to be healthy in other respects." Temporary lack of light is not a serious problem.

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The second effect of the suspended load is the smothering of organisms by deposits of sediment. Some corals have quite effective cleaning mechanisms (Wells, 1957; Yonge, 1930). Complete coverage can kill coral, but Edmondson (1928) and Mayer (1918) demonstrated that many species can live for more than a day when completely covered by a number of centimeters of sediment.

Marshall and Orr (1931) described experiments in which *Favia, Fungia, Psammocora,* and *Porites* showed little or no ill effects from being introduced into water containing 800 mg/liter of suspended mud. They quoted Mayer's (1924) observation that, under natural conditions, 3,700 mg/liter of suspended mud kills some corals, but suggested that the observed kill may have been related to decrease in salinity. Marshall and Orr (1931, p. 131) concluded that some species are more susceptible than others to deposition of sediment but that ". . . *Pocillopora, Galaxea, Symphyllia, Fungia,* and *Acropora* were all able to deal with large quantities of sediment under natural conditions, and it is difficult to believe that they can be killed by sediment falling from above." They of course dealt with growing colonies which may be able to withstand greater sediment deposition than could coral larvae trying to settle. The need for suitable substrate on which to settle is a problem to coral larvae in turbid, muddy environments.

Extensive coral reefs intimately associated with muddy sediments are present in Fanning Lagoon, both in clear and in turbid waters. An area in the turbid water was compared to one in the clear water to evaluate the effects of water turbidity on reef development.

The authors wish to thank H. G. Schiesser and G. L. Shepherd for their able assistance in collecting the data for this paper. K. E. Chave as leader of the expedition to Fanning Island deserves recognition for a job well done.

PHYSICAL SETTING

Fanning Island (3°55′ N, 159°23′ W) is in the central Pacific Ocean about 1,500 km south of Hawaii. Rainfall is about 200 cm per year, and there is a prevailing 10-knot east-to-southeast wind (Zipser and Taylor, 1968). The lagoon is ovate in shape, about 13 km by 6.5 km. It is landlocked except for three passes —two that are shallow, about 2 m, and one, English Harbor, which is up to 8.5 m deep. During the study period there was a net tidal influx of water into the lagoon through the two shallow passes and a net outflow through English Harbor (Gallagher et al., Pacific Science, this issue). Although large volumes of water moved in and out of English Harbor with the tides, there did not appear to be much mixing with the resident lagoon waters. Residence time of water in the lagoon was apparently about 11 months (Gallagher et al., Pacific Science, this issue).

A clear-water body was maintained in the lagoon in the vicinity of English Harbor (Fig. 1) and, at least on the north side, the contact between the clear water and the turbid, resident lagoon water was visibly sharp and distinct. Visibility in the clear water was about 10 to 15 m, while in the turbid water it was 2 m or less. The temperature and salinity of all of the lagoon water was about 28° C and 35 parts per thousand. This was about the same as the surface waters of the open ocean around Fanning Island.

A maximum lagoon depth of 18 m was encountered in the clear water. Depths were commonly 10 to 15 m in the clear water and 4 to 5 m in the turbid water. The maximum depth measured in the turbid water was 8.5 m.

Line reefs (narrow linear reefs) up to 200 m wide, crossed the lagoon and cut it up into a number of ponds approximately 1,000 m wide (Fig. 2). The tops of the line reefs were 0.5 to 2 m below the surface of the water. The azimuths were measured on sections of line reef 300 m long. There was a primary mode of azimuths perpendicular to the prevailing wind direction and a secondary mode parallel to the prevailing wind. Line reefs wider than about 20 m had a medial sand strip. The wider the line reef, the wider was the medial sand strip and the less abundant was the coral on the leeward edge. On reefs wider than about 100 m there was little or no coral on the leeward side. Sand drifting off the reefs built sand wedges into the pond on the leeward side of the line reefs. This caused the profile of the reefs to be asymmetric—steep slopes on the windward side

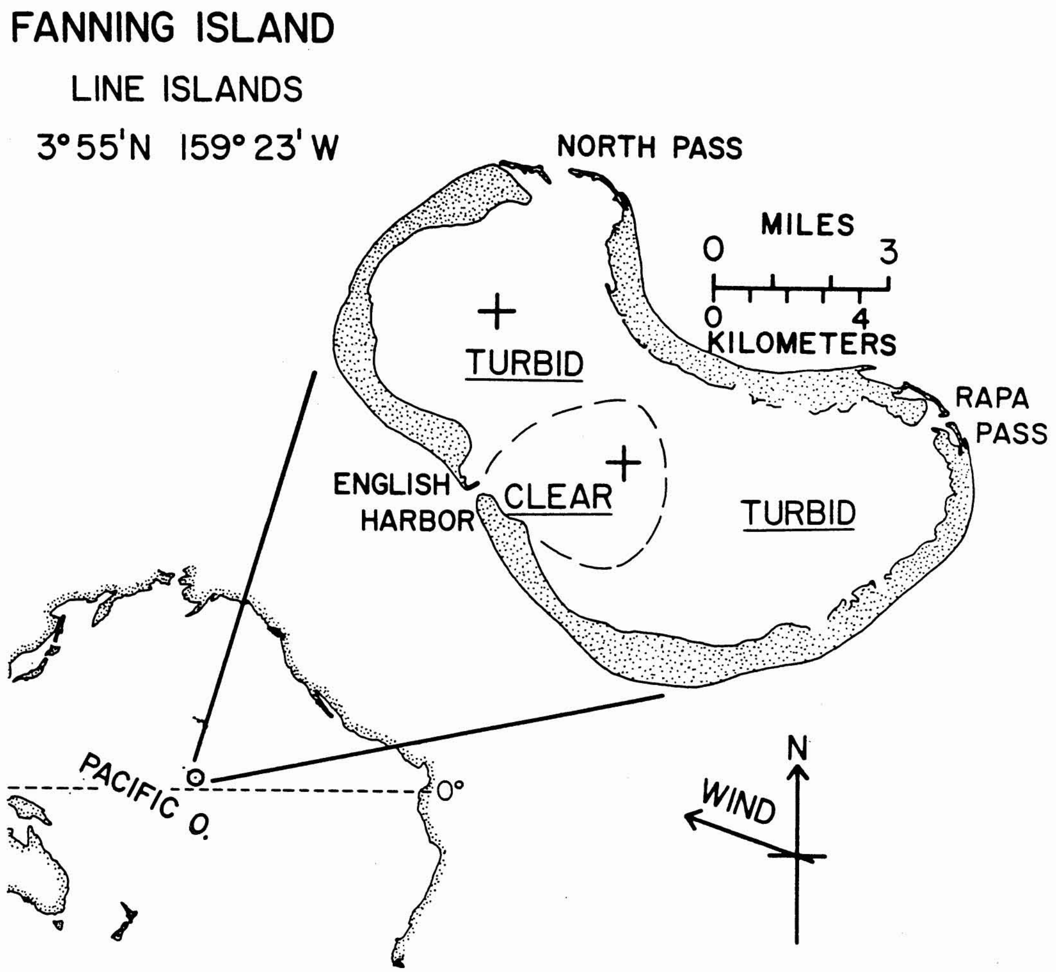

FIG. 1. Fanning Island. Crosses mark locations of benthic surveys in the clear- and turbid-water areas.

and gentle slopes on the leeward side (see Fig. 3).

The origin of the line reefs is not known. Although there were growth features that appeared to be related to present day wind and current patterns, the basic pattern may be related to karst topography formed during subaerial exposure of the island.

FIG. 2. Line reefs in Fanning Lagoon. The view was taken above North Pass looking toward English Harbor.

WORK DONE AND METHODS USED

In order to compare reef development in the clear and turbid waters, suspended load, light intensity, and bottom cover were measured in the two areas located approximately by the crosses shown on Figure 1. The area sampled

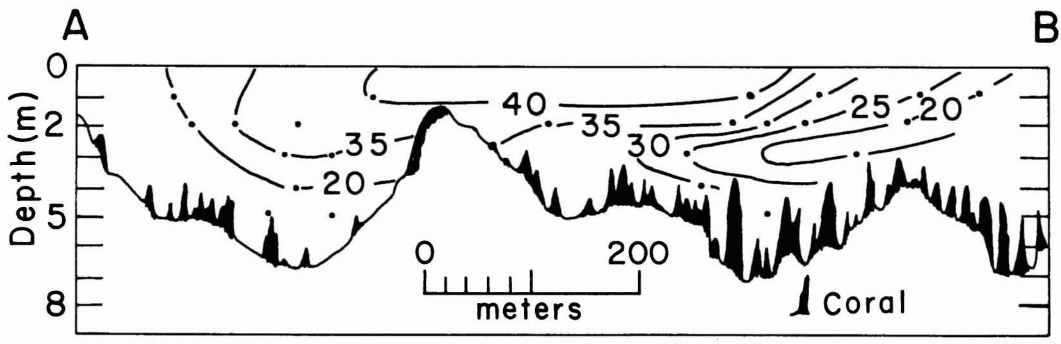

FIG. 3. A bathymetric and vertical extinction coefficient profile across the turbid-water pond. The line of section is shown on Figures 4 and 9. The extinction coefficients are in units of $\times 10^2$ per meter.

in the turbid water was a pond in the central part of the northern half of the lagoon. None of the passes into the pond were deeper than 1 to 2 m (Fig. 4). A channel (locally called Suez Channel) 6 m wide and 2 m deep had been dug across the line reef on the north side of the pond (Figs. 4 and 5). This particular pond was chosen as representative of the turbid water area of the lagoon. A few dives were made in other parts of the turbid area. These dives, together with numerous grab samples and the character of the bottom as shown on the fathometer traces taken in other areas, indicated that the pond was typical of the lagoon except for that part of the lagoon near shore. Shallow sand flats from 400 to 500 m wide were common around the edge of the lagoon.

The clear-water sampling area was chosen to duplicate the physiography of the turbid water pond as closely as possible. The area was also a pond of sorts, but the reef perimeter was less well defined here than in the turbid pond. The sampling area was on the periphery of the main clear-water area. Visibility in the water decreased markedly on the turbid water side of the line reef that marked the southeast side of the clear-water sampling area. The reef on the English Harbor side of the pond was 3 to 4 m deep. Passes into the central part of the clear-water area were up to 6 m deep.

Sediment samples were taken from the lagoon bottom with a van Veen-type sampler. Water samples were taken at the surface and at various depths using an *in situ* pumping apparatus (Schiesser, 1970). Chemical analyses were done on 163 samples to determine the calcium carbonate suspended load (Smith, et al., Pacific Science, this issue). Visible light intensity was measured with a Wesson submersible photometer. No filters were used. Twenty-two lowerings were done and readings were taken at 1-m intervals. Relative light intensities were calculated using synchronous deck and submerged cell readings. Vertical extinction coefficients (α) were calculated for 1-m depth intervals using the formula $[\alpha = -\ln (I_z/I_z - 1)]$.

Divers using SCUBA equipment determined the bottom cover at 0.25-m intervals on a 10-m long sampling line. The benthic survey was done at 22 localities in the turbid water and at 11 in the clear water. In all, 450 m of bottom in the turbid water and 200 m of bottom in the clear water were surveyed. A major problem arose in the benthic survey from the stirring up of the sediment into the water. Any agitation of the water near the bottom stirred clouds of muddy sediment into the water and reduced visibility to zero. The only workable way to sample was to lay the line down and swim along it—sampling ahead where visibility was adequate. This was the reason for using this "one-line" sampling method rather than grids.

Bathymetric surveying was done with a small boat and a Raytheon model DE-719 portable fathometer. Detailed surveys were made of both the clear and turbid water ponds. Bathymetric lines were also run in various other parts of the lagoon to determine the general nature of the bathymetry. Sample locations and survey track positions were determined by sextant fixes on objects on shore that could be located

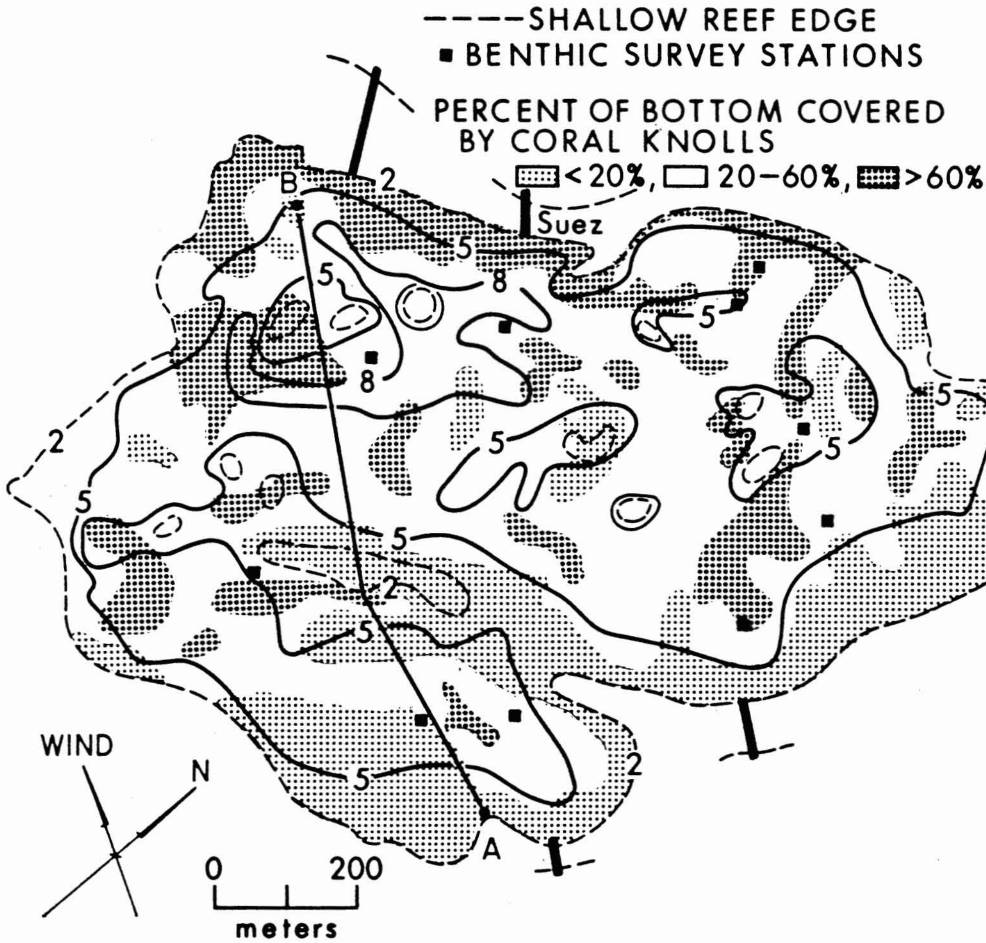

FIG. 4. Bathymetry and coral knoll abundance in the turbid-water pond. The line *A–B* is the profile shown in Figure 3. Contour interval is 3 m.

on the map of the island. For the detailed surveys and sampling locations in the ponds, local markers were set up, surveyed in, and used as reference points. In all, 9.5 km of continuous fathometer track were run in the turbid-water pond and 4.7 km in the clear-water pond.

The bottoms of the ponds were very irregular due to the presence of coral knolls. To arrive at bathymetric data which could be contoured, the depths were determined with reference to a generalized bottom trend arrived at by extrapolating the general bottom through all knolls. Coral knolls were arbitrarily defined as steep-sided areas greater than 2 m deep that rose higher than 0.3 m above the general bottom profile. Knolls that rose to within 1 or 2 m of the sur-

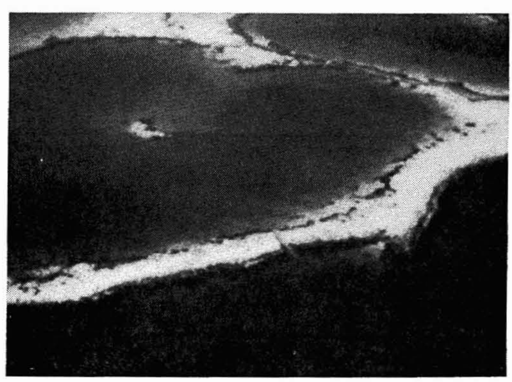

FIG. 5. Suez Channel across the line reef on the north edge of the turbid-water sampling area. The sampling area is in the foreground.

face were considered to be patch reefs. All dimensions associated with the coral knolls were measured with reference to the smoothed generalized bottom profile.

Widths of coral knoll crossings, heights of coral knoll crossings, and interknoll distances were determined from fathometer traces from the turbid-water and clear-water sampling areas. Lines of about equal length, one parallel and the other perpendicular to the direction of the prevailing wind, were used to obtain the knoll statistics. The data are summarized in Figure 6.

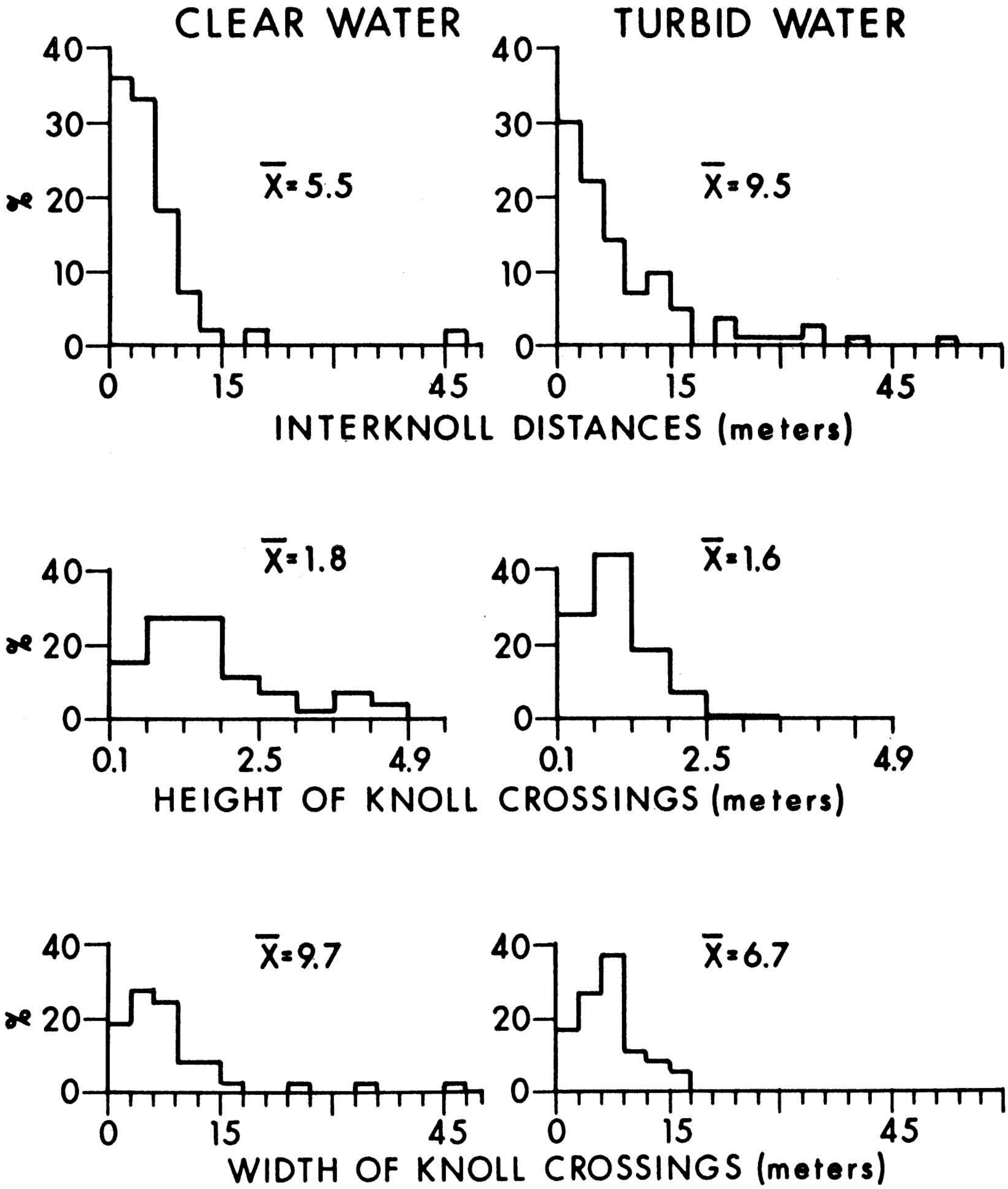

FIG. 6. Comparison of interknoll distance, height of knoll crossings, and width of knoll crossings in the clear- and turbid-water sampling areas.

Eight hundred and forty meters of track and 45 knoll crossings were used from the clear-water area, and 1,490 m of track and 73 knoll crossings from the turbid-water area. All the traces from the turbid-water pond were divided into 30-m intervals and the percentage of coral knoll in each interval was determined. These data were plotted and contoured (Fig. 4).

WATER TURBIDITY

Suspended Load

The calcium carbonate ($CaCO_3$) suspended load was about 3.5 mg/liter in the turbid water, about 1.0 mg/liter in the clear water, about 0.3 mg/liter in the water of the outside fringing reef (interpreted from the values in the inflowing water of English Harbor), and about 0.03 mg/liter in the open-ocean waters surrounding Fanning Island (Smith, et al., Pacific Science, this issue). The outside fringing reef was very well developed, and the suspended load of 0.3 mg/liter might be a representative number to expect for water associated with reefs of this type.

The suspended load $CaCO_3$ in the lagoon was about 65 percent aragonite and 35 percent calcite (X-ray diffraction analysis). The calcite fraction is a mixture of magnesian calcites. There are modes at 0 and 13 mole percent $MgCO_3$. The 13-percent mode is the major one. This distribution of aragonite, calcite, and magnesian calcites was very similar to that in the clay-sized fraction of the pond bottom sediments (Fig. 7). Most of the material in suspension was less than 6 μ in diameter. The modal size was 3 to 4 μ (petrographic microscope analysis). Large particles appeared to be cleavage fragments.

The suspended $CaCO_3$ appeared to be the product of biological and mechanical abrasion of skeletal materials on the reefs. Inorganic precipitation seems unlikely in view of the composition and appearance of the suspended material. The presence of extensive sand wedges in the lee of the line reefs is evidence of sand transport and, indirectly, of mechanical abrasion. Most coral skeletons in the lagoon showed evidence of extensive boring by sponges. Boring pelecypods were common. Much of the hard substrate showed evidence of fish grazing. In

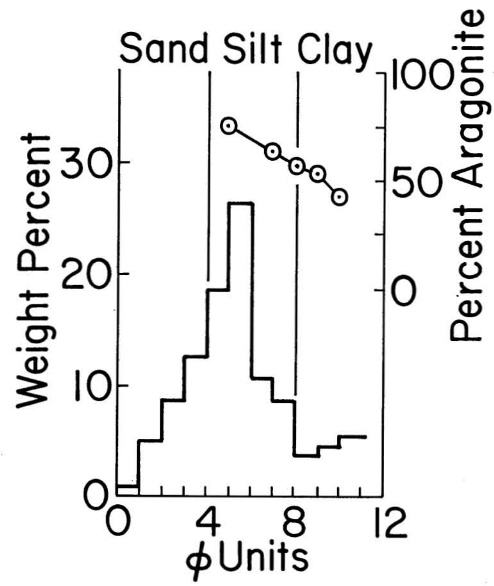

FIG. 7. Size and mineralogic composition of a representative mud sample from the bottom of the turbid pond.

Fanning Lagoon, as in many other areas, bioerosion was very extensive (Bardach, 1961; Gardiner, 1931; Neumann, 1966).

Light

At any given depth the relative light intensity was 10–20 percent higher in the clear water than it was in the turbid water (Fig. 8). In the turbid water, concentration of suspended $CaCO_3$ was high and the standard crop of plankton was large (Gordon, Fournier, and Krasnick, Pacific Science, this issue). Yet the minimum relative light intensity on the pond bottom was about 5 percent. There are two reasons for this. The depths were not great, so even with large absorption coefficients, much light penetrated to the bottom. Second, the fine-grained suspended material scattered light without greatly affecting the measured vertical extinction (Holmes, 1957). The mean extinction coefficient in the clearwater area was 0.13/m and 0.28/m in the turbid water. These values are about the same as extinction coefficients for green light in average oceanic and average coastal water (Sverdrup, Johnson, and Fleming, 1942).

According to Wells (1954), most coral reef

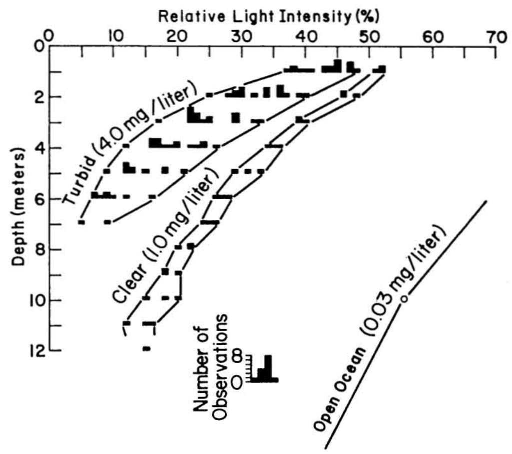

FIG. 8. Relative light intensity versus depth in the clear-water area, the turbid-water area, and the open ocean. The suspended load (e.g., 4.0 mg/liter) is the average weight of suspended $CaCO_3$ in each of the three areas. The relative light intensity in the open ocean is for an area off Hawaii.

growth occurs in depths of 30 m or less, although growth does continue down to about 100 m and at Bikini Atoll to about 160 m. Relative light intensity at 30 m in average oceanic waters is less than 1 percent (Sverdrup, Johnson, and Fleming, 1942). About the same amount of solar radiation reaches the sea surface at Fanning and Bikini atolls (Neumann and Pierson, 1966), so, at 5 percent, the relative light intensity at the bottom of the turbid pond was well above the minimum light requirements for reef growth. Light was not a limiting factor in reef development in the turbid water of Fanning Lagoon.

The distributions of extinction coefficients at various depths in the turbid pond showed definite patterns of variability (Fig. 9). In general the extinction coefficients in the surface water were large except in the downwind part of the pond. At intermediate depths there were minimum values, while below 4 m the extinction coefficients were essentially constant at values somewhat higher than the minimum.

Circulation in the pond was complex. The observations were taken on a falling tide. This may explain the relatively high values found in the surface water and around Suez Channel. Fine material taken into suspension over the leeward reef was moved out into the sampled pond by the tide. Suez Channel may be a region of maximum volume transport of water across the reef during the tidal cycle. This could explain the tongue of turbid water upwind from Suez.

The extinction coefficient profile across the turbid pond (Fig. 3) suggests the following simplified circulation model. The wind drives surface water over the windward reef and sediment is put into suspension. The water moves across the pond; the suspended material settles, leaving the surface water of the downwind side of the pond less turbid. Then the surface waters reach the leeward reef, some of the water goes over the reef into the next pond and some sinks and flows upwind at depth to replace the water upwelling on the upwind side of the pond. Dye experiments indicated upwind water movements at depth (Gallagher et al., Pacific Science, this issue). The return flow appeared to be at about 3 m in depth. Below 3 m the flow was restricted by coral knolls (Fig. 3). Coral thickets acted as baffles. Mud between *Acropora* branches on the knolls was finer than the mud of the interknoll areas.

BOTTOM TYPES

The sampled areas can be divided into three categories: pond bottoms, reef slopes, and reef flats. These areas had distinct boundaries and, in most cases, distinct bottom characteristics with respect to the nature and type of coral cover, and sediment type and distribution (Table 1).

Sediments

The sand on the reef flats of both areas was coarse- to medium-grained. Because the reef tops were shallower in the turbid water than in the clear water the sand on the turbid water reefs tended to be finer and better sorted. On the lee side of the reefs there were distinct wedges of muddy sand that extended out about 60 m into the pond before grading into the mud of the pond bottom. The pond bottom muds had a silt-sized mode (Fig. 7). Sand wedges were not found in the clear-water area examined although the mud at the base of the reefs was sandier than in the central part of the clear-water pond. Apparently little sand was produced on the clear-water reef flats. This may be a function of their deepness.

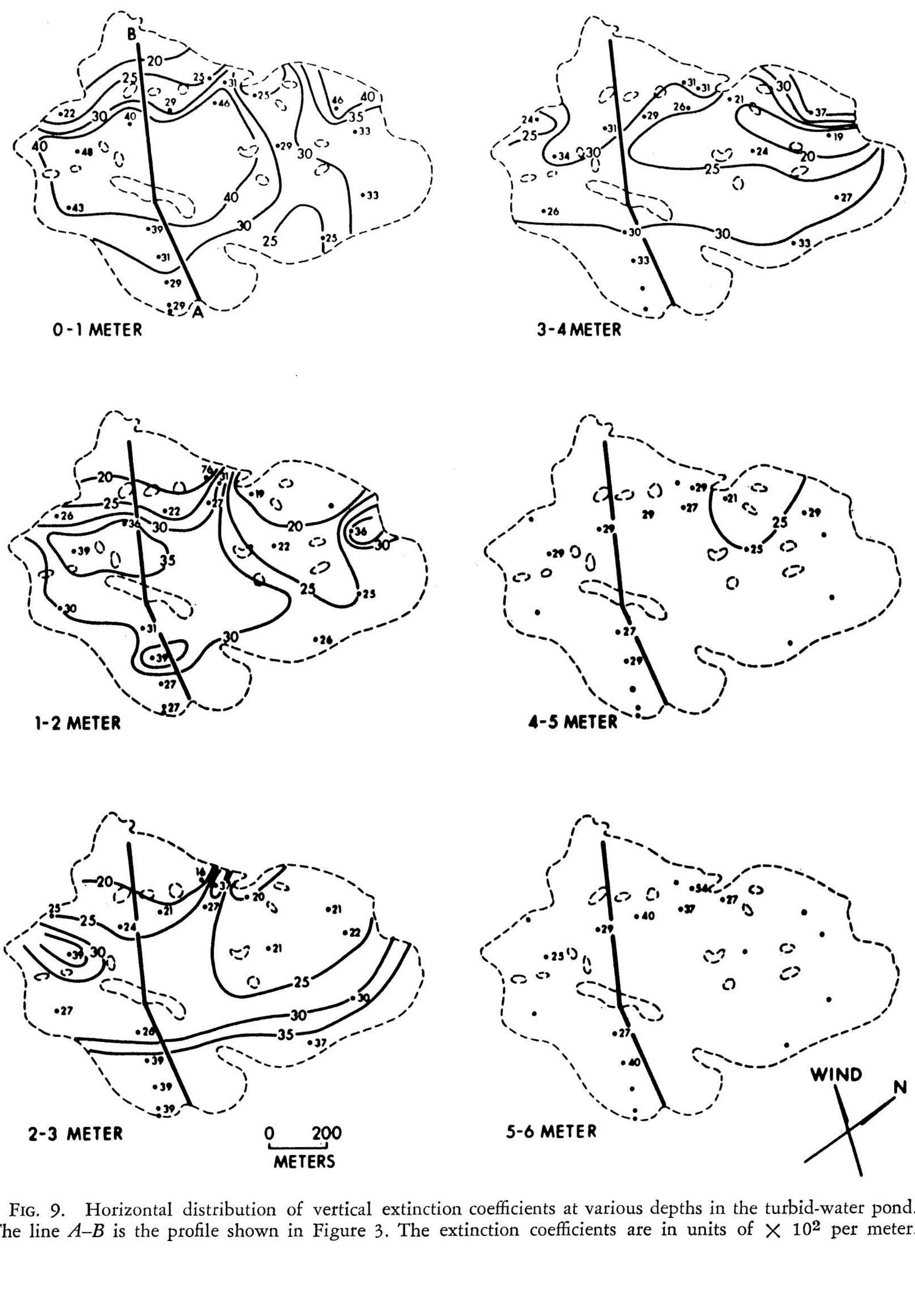

FIG. 9. Horizontal distribution of vertical extinction coefficients at various depths in the turbid-water pond. The line *A–B* is the profile shown in Figure 3. The extinction coefficients are in units of $\times 10^2$ per meter.

TABLE 1

BOTTOM CHARACTERISTICS OF FANNING LAGOON

	LIVING CORAL (%)	DEAD CORAL AND CORAL RUBBLE (%)	ENCRUSTING CORALLINE ALGAE (%)	SAND (%)	MUD (%)	LIVING *Monti-pora*** (%)	LIVING *Acropora* (%)	LIVING RAMOSE CORALS (%)
Turbid Water								
Pond Bottom *	35	10	1	0	54	21	41	46
Reef Slope	28	35	2	35	0	0	78	96
Reef Flat	21	29	9	41	0	1	51	71
Coral Knolls	78	——22——						
Clear Water								
Pond Bottom	59	13	0	0	28	57	0	1
Reef Slope	73	7	11	1	8	75	2	5
Reef Flat	46	15	15	24	0	48	21	38
Coral Knolls	83	——17——						
Averages †								
Turbid Water	31	21	3	73	27	13	55	55
Clear Water	62	12	7	4	17	52	5	10

* The pond bottom includes coral knolls as well as areas of sediment. The division "coral knolls" is a subdivision of the pond bottom.

** Figures represent percentage of the living corals that is *Montipora*.

† The values are weighted averages, using 50 percent pond bottom, 32 percent reef slope, and 18 percent reef flat as the relative percentages of the various lagoon areas. The percentages were obtained from analysis of the bathymetric map of the turbid pond. The same weighting was used for the clear- and the turbid-water areas.

The micromollusc fauna in the pond muds was distinct from that on the reef flats (Kay, Pacific Science, this issue). Foraminifera were present in the lagoon muds, and their abundance appears to be a function of nearness to coral knolls. There were an average of 310 foraminifera tests per gram of sediment. There were few species, and, of these, *Ammonia beccarii tepida* was the most abundant (J. Resig, personal communication). Both the number of species and the number of individuals were low compared to other atolls (Emery, Tracey, and Ladd, 1954).

Another organism that is common on other atolls but rare in Fanning Lagoon is *Halimeda*. Live *Halimeda* plants were seldom seen in the lagoon. Emery, Tracey, and Ladd (1954) gave 36 percent *Halimeda* and 5 percent foraminifera tests as the composition of the average sediment from four lagoons in the Marshall Islands. In Fanning Lagoon both *Halimeda* and foraminifera made up less than 1 percent of the volume of the sediment. The reason for the low abundance is not known.

Alcyonarians were present in small numbers in both the clear and the turbid waters of the lagoon and red alcyonarian spicules were noticeable in many turbid water area mud samples. On the average there were 350 spicules per gram of mud. The alcyonarians live on the coral knolls. Alcyonarian spicules and foraminifera tests made up comparable proportions of the sediment.

Coral

Bottom cover by coral in the clear- and turbid-water areas differed in amount and in type (Table 1; Figs. 10, 11, 12). Live coral covered about 60 percent of the bottom in the clear water and about 30 percent in the turbid water. Figure 13 shows the distribution of live coral cover with depth as determined by the benthic surveys. Although the coverage was almost constant with depth in the clear water, there were large changes with depth in the turbid water.

The low abundance of coral at shallow depths was due to lack of coral on the reef flats. Reef flats sampled in the clear water were all greater than 1 m deep thus explaining the relatively high values for coral cover relative to the 0.5-m-deep reef flats in the turbid water.

Coral knolls in the turbid water had about

FIG. 10. A massive coral knoll in the clear water. The shark prod is 2 m long.

80 percent live coral cover according to the benthic surveys (Table 1). The knolls covered 37 percent of the area of the pond bottom (Fig. 4). These figures yield an average coral cover of 30 percent—the same as the estimate derived from the benthic survey data (Table 1). Thus, mapping the distribution of coral knolls using the bathymetric data gives a more detailed picture of the distribution of coral in the turbid water than is possible from the relatively few benthic survey stations occupied. The coral knolls had a distinct, though irregular, distribution pattern: low abundance in the upwind part of the pond, and increasing abundance downwind.

The general pattern can be explained using the previously discussed model of sedimentation in the pond. Coral was killed by deposition of sediment in the upwind portion of the pond.

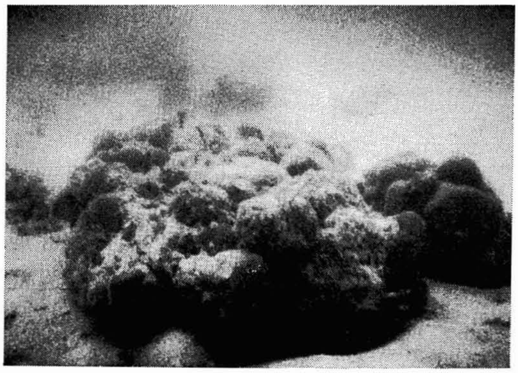

FIG. 11. A massive coral knoll in the turbid water. The knoll is 2 m wide.

FIG. 12. *Acropora* and calcium carbonate mud on a coral knoll in the turbid water. The view covers about 1 m.

The deleterious effect decreased downwind, and maximum knoll development occurred along the downwind edge of the pond. In general the distribution of coral knolls appeared to result

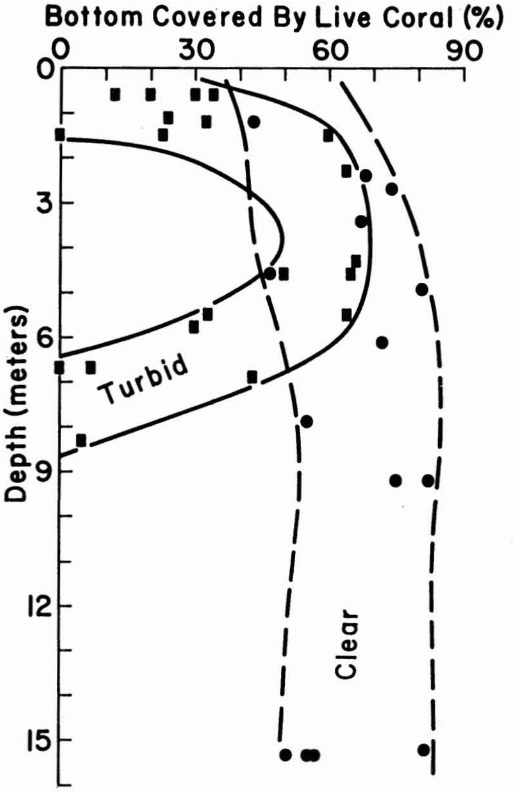

FIG. 13. Coral cover at various depths in the clear- and turbid-water areas (benthic survey data).

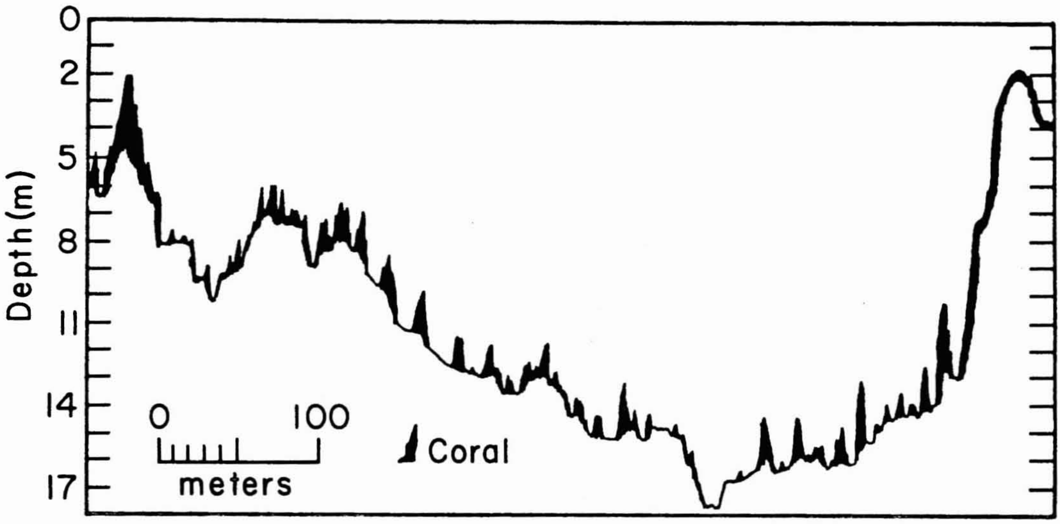

Fig. 14. A bathymetric profile in the clear-water sampling area.

from progressive decrease in the amount of deposition of material away from the upwind edge of the pond and by encroachment of the sand wedge into the pond.

The apparent discrepancy between Figure 14 which shows less than 10 percent live coral cover in the turbid water deeper than 6 or 7 m, and Figure 4 which shows the area deeper than 8 m to be 20 to 60 percent coral knoll has two explanations. The area below 8 m depth shown on Figure 4 was actually between 20 and 30 percent coral knolls, with much of it closer to 20 percent. Also, it is possible that the three deeper, low-coral-cover stations could have missed coral knolls by random chance. It seems that there were two effects operating to restrict knoll development in the pond. One was the encroachment of the sand wedge into the pond, and the second was the uniform settling of fine material out of suspension. This last mechanism was not very effective except in the deeper areas of the pond where the bottom physiography caused water movements to be restricted.

BOTTOM PHYSIOGRAPHY

The trend of the line reefs perpendicular to the prevailing wind was reflected in the bathymetry of the turbid pond bottom even in ridges that did not reach within a meter of the surface. Over most of the turbid pond the coral knolls with up to 3 m relief covered about 37 percent of the bottom. The average knoll crossing in the turbid water was 1.6 m high and 6.7 m wide and the average interknoll distance was 9.5 m (Fig. 6). In the clear water the same statistics were 1.8 m, 9.7 m, and 5.5 m. There was little difference in the size of knolls in the clear and in the turbid water, although the mean crossing width in the clear water was larger due to the presence of a few very large knolls. In each case the dimensions parallel and perpendicular to the prevailing wind were very similar so the knolls appeared to be more or less equidimensional in plan view. The average interknoll distance in the clear water was about one-half that in the turbid water, perhaps reflecting the less favorable environment in the turbid water.

What the average crossing dimensions meant in terms of the actual average knoll dimensions is a problem. If the knolls are approximated by hemispheres the average crossing dimensions were 0.85 the actual average dimensions. The knolls were more closely modeled by rectangular prisms so that the average crossing dimensions may be somewhat conservative but should be within 5 to 10 percent of the actual average dimensions.

SPECULATION ON AGE OF TURBID ENVIRONMENT

The interpretation of the turbid-water coral reef development is tempered by uncertainty about the age of the environment. Are the reefs actually developing in the turbid water or are they merely a degenerate skin on a relict topography? The environment is at least 150 years old, as no mention of major change has been made in the recorded history. Beyond that, there are no definitive data. There are, however, observations that allow speculation.

The distribution of land around the rim of Fanning Atoll was peculiar. Much of the windward area was swampy intertidal or shallow subtidal (Guinther, Pacific Science, this issue). Nearly all of the leeward area was land. The windward fringing reef was about the same width as the leeward reef. Both the reef widths and the land distribution were the reverse of what is generally found on atolls (Wiens, 1962, p. 41). Rapa Pass appeared to have been formed by the breaching of a conglomeratic beachrock ridge. Erosional remnants of the beachrock occurred for some distance out onto the reef flat in the vicinity of Rapa Pass. These observations suggest that the atoll is tilting upward to the west. This tilting, of course, would change the configuration of passes around the lagoon and circulation within the lagoon.

Tilting could explain the infilled pass at the site of the Cable Station. The two spits on the lagoon side at the Cable Station were cemented shingle with well-developed imbricate structure. The imbricate structure of the two spits had opposing dips and strikes into the lagoon. The unconsolidated sediment filling the old pass is interpreted to be younger than the phosphatized conglomerates making up this part of the atoll rim.

Another feature that appeared to be of fairly recent origin is the complex of apparent relict tidal deltas that occurred at the lagoon edge about 5 km west of Rapa Pass (See Fig. 1 in Guinther, Pacific Science, this issue.) There was a free flow of water through this area but the path was rather tortuous. It seems unlikely that the features could have formed under the present regime. The short distance from the open sea to the deltaic features was blocked by a long, narrow, boulder ridge. If both the southern pass and the Cable Station pass were open, circulation in the lagoon would be different and perhaps the water would be less turbid. The Cable Station pass appeared to have been similar to the present English Harbor pass, so conditions in the lagoon by the Cable Station pass may have been similar to those now found in the vicinity of English Harbor.

Along the lagoon shore about 500 m south of the Cable Station pass was a temple reported to have been built in the 16th century (Emory, 1939). On the shingle ridge on the south side of the pass there were graves that appear also to be 16th century. It is not clear whether the pass was open at the time the temple was built. At present canoes can land from the open sea in the vicinity of the Cable Station. This, plus the availability of building stone in the area, may explain the location of the temple without requiring that the pass be open. The graves, however, were on the shingle ridge so the pass existed at least 400 years ago.

This period is not long geologically, but is long enough to have allowed the turbid water community to stabilize. This community has produced at least a meter of apparently continuous reef growth on the line reefs. If this growth has occurred over 400 years, then the net production is comparable to other coral reef areas (Smith, 1970; Chave, Roy, and Smith, Pacific Science, this issue). This does not say that the present coral reef configuration in the turbid water area is not undergoing progressive degeneration. Although the corals themselves generate new substrate suitable for larval settlement, it seems that the general trend, however slow, is to decrease the favorable area through encroachment of sediment on the hard substrate. In a closed area, through time, reefs will bury themselves in their own debris unless the rate of sea level rise is sufficient to accommodate skeletal production.

CONCLUSIONS

Although coral reefs will not develop in environments with less than some minimum light intensity and more than some maximum sediment deposition rate, these requirements are less stringent than is generally realized. Extreme water turbidity and muddy bottoms do not necessarily mean that the limiting values are exceeded.

Reef development in the turbid water of Fanning Lagoon was of the same magnitude as it was in the clear water. Coral knolls had about the same dimensions in both areas although they were less abundant in the turbid- than the clear-water area. In both areas the knolls are surrounded by calcium carbonate mud.

Only four of the coral species that were found in the clear water were not found in the turbid water (Maragos, Roy, and Smith, 1970). The major difference in the coral fauna was in the relative abundance of individuals of a species and in growth forms present. In the turbid water ramose growth forms made up 50 percent of the individuals while in the clear water they made up only 10 percent.

Although the reefs of the two environments differed from one another ecologically, stratigraphically they were similar in form and in distribution. Because of the difference in faunal composition, the reefs in the turbid water tended to be structurally different from those in the clear water. Clear-water reefs are made up primarily of encrusting and massive corals. The reefs tended to have vertical walls and overhangs, and were massive (Fig. 15). The turbid-water reefs, because of the abundance of ramose growth forms, tended to be more open, to have gentler slopes, and to be infilled by fine sediment as a result of the baffling effect of the corals on the knolls.

In conclusion, Fanning Lagoon was an area where visibility in the water was about 2 m, where suspended load was about 100 times that of the open ocean, where the bottom was covered with calcium carbonate mud, where depositional rates appeared to exceed 1 mm/year, and where about 30 percent of the bottom was covered with live coral. Though there was a decrease in abundance of coral knolls from the clear to the turbid water, both areas had lush reef development. If the lagoon were to fill, it would produce a limestone body composed of areas of coral biolithite surrounded and, in part, infilled by calcilutite. The fine-grained rocks would be penecontemporaneous with the biolithite and never would the bathymetric relief exceed 8 m.

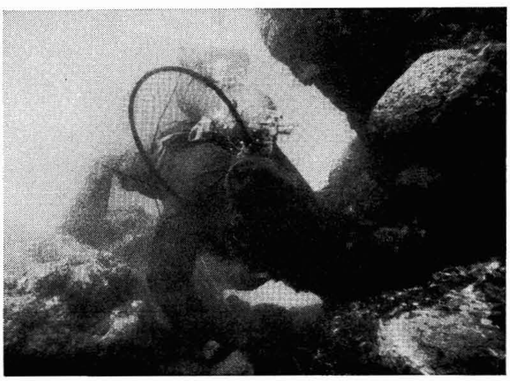

FIG. 15. A diver doing a benthic survey along the edge of a clear-water knoll.

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