EFFECTS OF OFFSHORE OIL DRILLING ON PHILIPPINE REEF CORALS

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ABSTRACT

An offshore drilling site in an area of extensive live-coral bottom off northwest Palawan Island, Philippines, was examined 15 months after well completion to determine effects of drilling on coral growth and survival. Core samples of 38 *Porites lutea* head corals were collected from around the drilling site and from a control reef and their histories compared using X-radiography to reveal changes in annual growth before, during and after drilling.

Analysis of *P. lutea* growth rates showed that when compared to their pre-drilling growth averages and to growth of corals from a nearby control reef, little suppression of head coral growth could be attributed to drilling. Diver observation, however, together with analysis of sampling transect photomosaics, revealed an estimated 70 to 90% reduction in foliose, branching, and plate-like corals in an iron-stained area that extended out from the wellheads in a 115 × 85-m ellipse. Coral cover beyond this area was comparable to that of the control reef.

Man's continuing dependence on fossil fuels as a primary energy source has forced expansion of oil-drilling exploration further and deeper into the World's oceans in the last 2 decades. Critical to the drilling is a bentonite clay and lignosulphonate-based fluid (drill mud) often containing barite to increase specific gravity. The mud is pumped downhole to lubricate and flush out rock cuttings excavated by the drill bit and to prevent blowouts. At the surface, the drill mud is separated from the cuttings and recirculated back downhole. The mud-coated cuttings are discarded into the water, and as the cuttings settle to the seabed, much of the mud washes off to form a visible plume. Sometimes, such plumes travel downcurrent and are visible for a kilometer or more. Periodically, excess mud must be discarded because of buildup of sand in the mud pits. During these discharges, as well as during discharges that result from well completion, up to 5,000 barrels of drilling mud may be discharged in a few hours. Various chemical additives are included in the mud mixture to overcome specific problems encountered during drilling. A number of these substances, especially the biocides, are highly toxic to many life forms. In spite of considerable research, what effect these discarded materials have on the marine environment is, today, still poorly understood.

A 1975 symposium entitled "Environmental Aspects of Chemical Use in Well Drilling" was the first major attempt to address the question of possible harm to the environment by drill mud and its additives. From this meeting evolved numerous research projects to assess effects of drilling muds and drilling-mud additives on both terrestrial and aquatic ecosystems. A second symposium, "Research on Environmental Fate and Effects of Drilling Fluids and Cuttings," held in 1980, brought together results of past and ongoing studies dealing with possible effects of these materials on the environment. Much of the research on fate and effects of drilling fluids in the oceans has been devoted to those organisms least able to escape its effects, notably bottom-dwelling and sessile forms. Chief among these are reef-building corals that, ironically, are often found to be growing near or directly over salt domes or deeply buried antecedent reef deposits that contain commercially significant quantities of oil or gas.

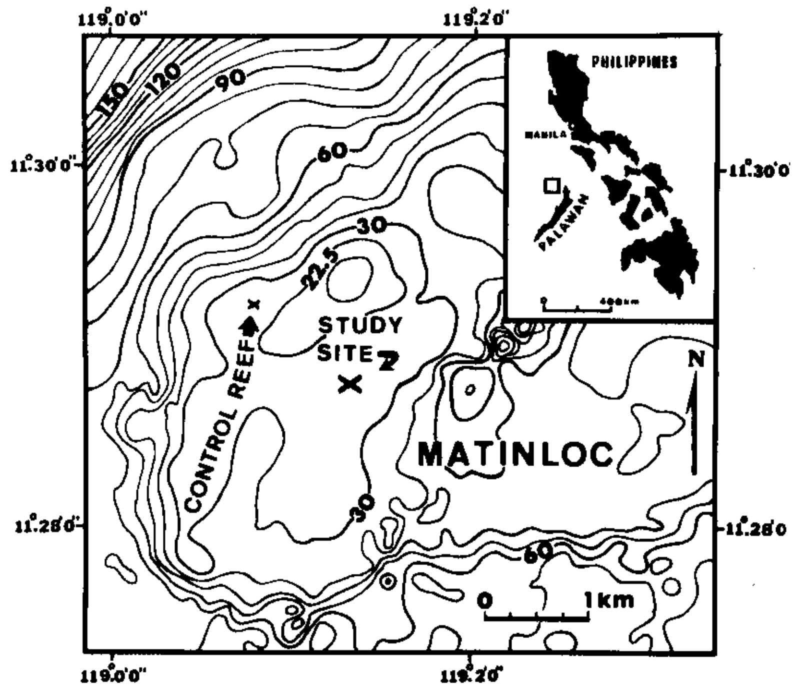

Figure 1. Location map of Matinloc study area. Water-depth contours are in meters. Unmarked isobaths = 7.5 m.

At present, drilling operations in areas of coral reefs have been conducted or are planned in the Gulf of Mexico (Flower Garden Banks), western Atlantic (Marquesas Keys), the Caribbean (Trinidad), Arabian Gulf (off Abu Dhabi), and the South China Sea off Sarawak (eastern Malaysia) and Palawan (Philippines). The Flower Garden Banks in the northeastern Gulf of Mexico is an excellent example of reef corals growing near oil-producing formations. This unique area, more than any other, has been a focal point of controversy and, more recently, of research on the advisability of oil exploration in areas of coral reefs.

A literature review by Dodge and Szmant-Froelich (in press) on effects of drilling fluids on reef corals clearly indicates that although considerable knowledge has been gained thus far, an approach to experimental design is needed in the laboratory that would more closely approximate actual water-quality conditions at a drilling site. What these conditions are can best be determined by on-site monitoring of changes in water quality during drilling operations in various ocean environments and water depths. Obviously, a stronger data base on water-quality variables needs to be established before we can extrapolate more definitive answers from laboratory experimentation.

An alternate approach to determine the nature and extent of damage to coral fauna by drilling activities is on-site examination of an area where drilling has been done directly on a coral reef. This direct-approach method was recently applied to study the impact of commercial drilling operations on reef corals off northwestern Palawan Island, Philippines. This study, believed to be the first of its kind, is the subject of this report.

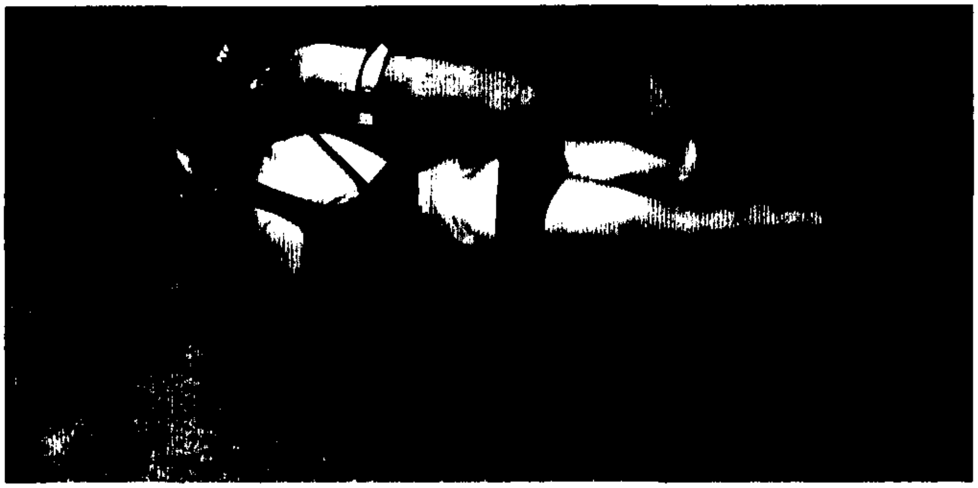

Figure 2. Spur-and-groove reef formation at Matinloc. Diver is swimming parallel to groove filled with coarse reef sediment. Note large sand ripples at right.

Study Area

The study was conducted during May and June 1981 at Philippines-Cities Service Matinloc Field Wells No. 1 and 2 (11°28′45″N, 119°01′20″E). The site is in 26 m of water approximately 50 km northwest of Palawan Island, Philippines (Fig. 1). Two exploratory wells less than 3 m apart were drilled at Matinloc. Well No. 1 was drilled between November 1978 and January 1979; Well No. 2 was begun in January 1980 and completed in March of that year. Both wells had oil-producing horizons, but a production platform to recover the oil had not been erected at the time of study. The wellhead location is marked at the surface by a large steel buoy held on station by approximately 60 m of iron chain secured to a 1,000+-kg stock-type anchor.

Site Description

The well site is in the midst of a highly diverse hard-coral community that has evolved into a distinct but low-relief spur-and-groove pattern. A thin but profuse veneer of foliose, branching, and plate-like corals dominate the flat coralline outcrops. Also present but in less abundance are numerous species of massive head corals. The low-relief (less than 50 cm high), linear coral patches are separated by intermittent 1- to 4-m-wide sand channels filled with coarse coralline sand and reef rubble. Coral spurs and sand-channel grooves are oriented in a north-northeasterly direction (Fig. 2) and are parallel to the effective or prevailing wind and current direction.

Environmental Conditions

Hydrologic conditions in the Matinloc area are generated and maintained by converging wind systems that create the monsoons, strong (11–17 knots) uni-directional winds that blow from the northeast during October to May and from the southwest during June to October (Ritchie, 1968). These winds strongly influence direction and strength of surface currents, as well as wave height and direction (Fig. 3). Tidal range is minimal and has little effect on current strength or direction. Severe tropical storms (typhoons) are common and are most likely to occur during the southwest monsoon season. These catastrophic storms (the equivalent of hurricanes in the Atlantic) are known to play an important role in coral-reef ecology (Stoddart, 1963; 1965; Ball et al., 1967; Perkins and Enos, 1968; Woodley et al., 1981). Waves 3 m in height occur frequently during both monsoon seasons.

Sea surface temperatures in the Matinloc area are very constant, ranging from 26.7°C to 29.5°C with a mean of 28.4°C (Wyrtki, 1961). Surface-water temperatures are reportedly constant to a depth of 50 m. In this study, divers did not experience thermoclines at any depth, including a dive to 46 m under an oil-production platform.

Field work at Matinloc was timed to take advantage of moderating sea and weather conditions that prevail during May between monsoon seasons. Only weak (less than 3 cm/sec) north-flowing currents

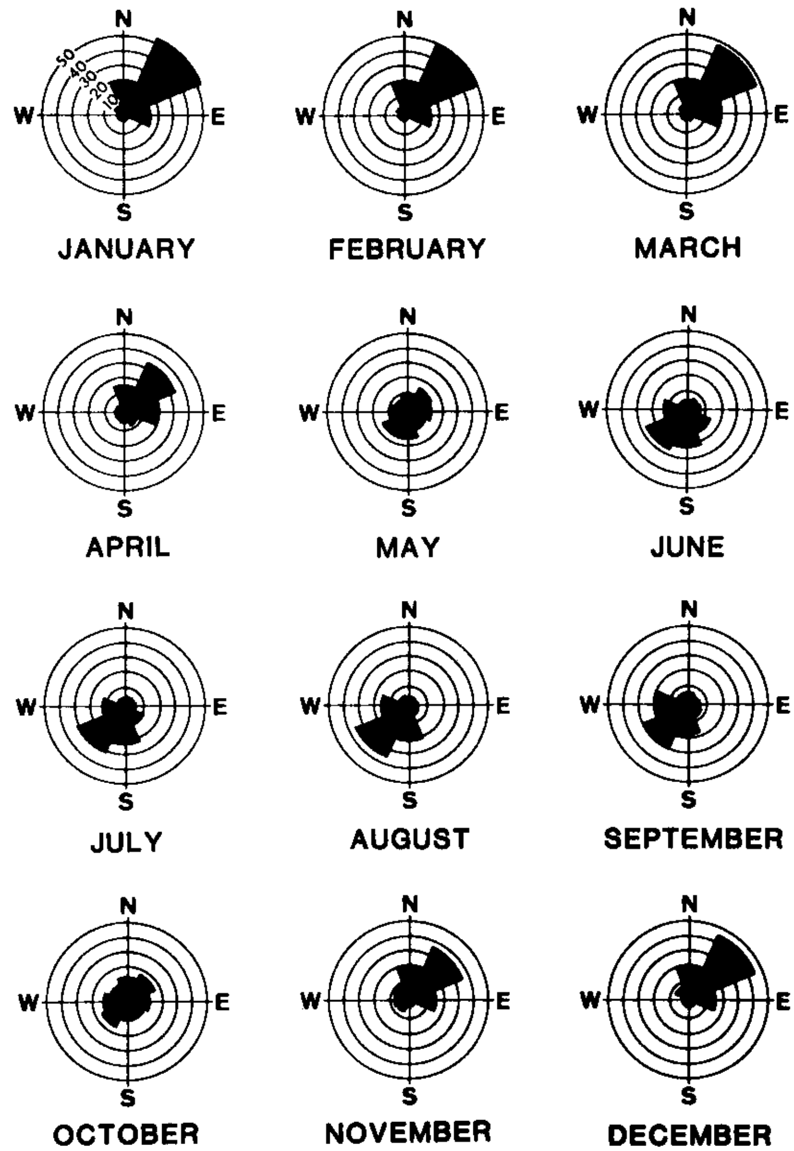

Figure 3. Average frequency of wind direction by month, January–December, offshore Palawan Island, Matinloc area. Rings indicate frequency of direction by percent (see January). Data from Naval Weather Service Command (1973).

were found during the entire study. Winds were light and sea conditions generally calm. Water clarity was excellent with horizontal visibility ranging from 20 to 40 m.

Marking the exact point of drilling penetration are two conductor pipe casings (wellheads) less than 3 m apart that project vertically approximately 5 m above the seabed (Fig. 4). The inner and outer walls of the open pipes are festooned with encrusting organisms, including the soft coral *Dendronepthya* sp., and numerous unidentified algae and sponges. Live-coral cover within 25 m of the wellheads was estimated to be less than 10%. Within this area, the codiacean alga *Halimeda* appeared to be a successful competitor for attachment on exposed rocky outcrops and reef rubble. Many of the corals observed appeared to be newly recruited species and included *Porites lutea*, *Cyphastrea serailia*, *Pocillopora* sp., *Goniastrea* sp., *Ceptoria phrygia*, and *Acropora* sp. A notable exception was a 30-cm-high colony of *Cyphastrea serailia* growing less than 10 m from the west side of the wellhead pipes (Fig. 4). The upper ⅓ of this head coral was dead; however, the remainder of the coral was living. Estimates of live- versus dead-coral cover around the wellheads were made from underwater photomosaics and are conservative with respect to live coral because many small or otherwise inconspicuous forms undoubtedly went unnoticed.

Coral cover comparable to that found at a control reef 1.25 km distant (Fig. 1) was found at the following distances from the wellheads: north—38 m; south—50 m; east—65 m; and west—50 m. In areas of undisturbed coral, the ratio of foliose, branching, and plate-like corals to massive species was estimated (from photomosaics) to be 10:1.

Methods and Materials

Fundamental to coral growth history analysis (sclerochronology) is the premise that coral growth rates are influenced by changes in the environment (Hudson, 1981). Growth rate increases to an optimum level when conditions are most favorable and conversely declines when conditions are poor.

Porites lutea was selected for study because of its well defined growth bands, relative abundance around the drilling site and nearby control reef, and because previous research has documented the annual nature and approximate timing of density band formation in this species (Buddemeier et al., 1974). Thus, in order to evaluate coral growth rates before and after the drilling operations, a series of cores were taken from living *P. lutea* head corals along transect lines that radiated north, south, east, and west from the wellheads. Divers used a hand-held compass and white nylon cord marked at 1-m intervals to position each of the 100-m-long transect lines accurately. The line was tied to the pipe that marks the location of Well No. 1. For this study, both wells can be considered as one because of their proximity to each other. In addition to 1-m increment marks, 3 × 4-cm tags numbered from 0 to 100 were attached every 5 m to the nylon cord to serve as visual location markers for sampling and photography. After each transect was laid out, corals to be cored were marked with pre-numbered styrofoam floats, which were anchored with cord so that the marker floated about 1 m above the coral head (Figs. 4, 5). Corals 15 cm or more in height (thus insuring a pre-drilling growth record) and having living tissue on their uppermost growth surface were marked for coring as they were found along the transect lines. All corals were cored at their apex, the area of maximum vertical growth. We were unable to sample corals at evenly spaced 10-m intervals as planned due to the irregular spur-and-groove pattern of reef growth and patchy distribution of *P. lutea*.

After the corals were cored, the coded plastic floats were left in position and a series of overlapping 35-mm underwater color photographs were taken for the entire 100-m transect. The photographs were fitted together to make a photomosaic similar to the familiar aerial photomosaics used in map making. Using the photomosaics, we could locate the numbered corals that had been cored and measure their distance from the wellheads. Portions of the north and south transects are shown in Figure 5.

In addition to *P. lutea*, other species of head coral were cored, including *Goniastrea* sp. and *Cyphastrea serailia*. Unfortunately, these specimens did not contain sharply defined yearly growth bands and thus could not be included in the growth-rate analyses.

Core sampling was done with a small hand-held Stanley[1] hydraulic drill and a 4-cm-diameter × 20-cm-long diamond-tipped core barrel (Fig. 4). Power to the drill was supplied by a gasoline-driven hydraulic pump via two 5-cm-diameter × 60-m-long hydraulic hoses. All cores were labelled immediately after recovery and returned to the surface for storage and shipment back to the laboratory for processing. In the laboratory, a rock saw was used to section each core sample into thin (3-mm-thick) slabs along the axis of corallite growth. Core slabs were placed on X-ray-sensitive film and exposed to an X-ray source of 3 Ma at 60 kVP for 90 sec. Exposed films were processed and contact X-radiograph prints made on high-contrast paper for growth-rate analysis.

Growth-rate measurements were recorded using the following procedure. Clear, 0.003-mil drafting acetate was taped over each X-radiograph print and a fine ink line drawn along the major axis of corallite growth. Yearly growth increments were marked off along the vertical ink line with an ink (tick) mark at the crest of each high-density growth band. Growth increments were measured to the nearest 0.01 mm using a precision caliper with dial readout. Figure 6 shows a typical X-radiograph.

Estimates of when, during the year, high- and low-density band couplets are deposited in *Porites lutea* at the Matinloc site were made on the basis of findings by Buddemeier et al. (1974), who studied growth rates of this and other species at Enewetak Atoll, Marshall Islands. By sampling at various times during the year and noting X-rayed samples, they concluded that low-density bands in Enewetak corals "began some time during the period December–January and ended about July." Thus, high-

[1] Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Figure 4. Diver coring damaged head coral, *Cyphastrea serailia*, with rotary hydraulic drill. Note wellheads (arrows) and styrofoam marker float in background.

density banding in *P. lutea* would be initiated about July–August and would end in January. Because yearly growth increments are measured from crest to crest of high-density bands, January was selected as an approximate time horizon for purposes of growth-rate studies at Matinloc.

RESULTS

Evidence derived from diver observations, together with examination of photomosaics detailing 400 m of reef transect at Matinloc Field, indicates that a 70–90% reduction in live coral cover at the drill site extends from the wellheads in an elliptical pattern: 35 m north, 50 m south, 65 m east, and 50 m west (Fig. 7). Coral cover beyond these distances is comparable to that of an undisturbed control reef in the same water depth 1.25 km northwest of the study site (Fig. 1).

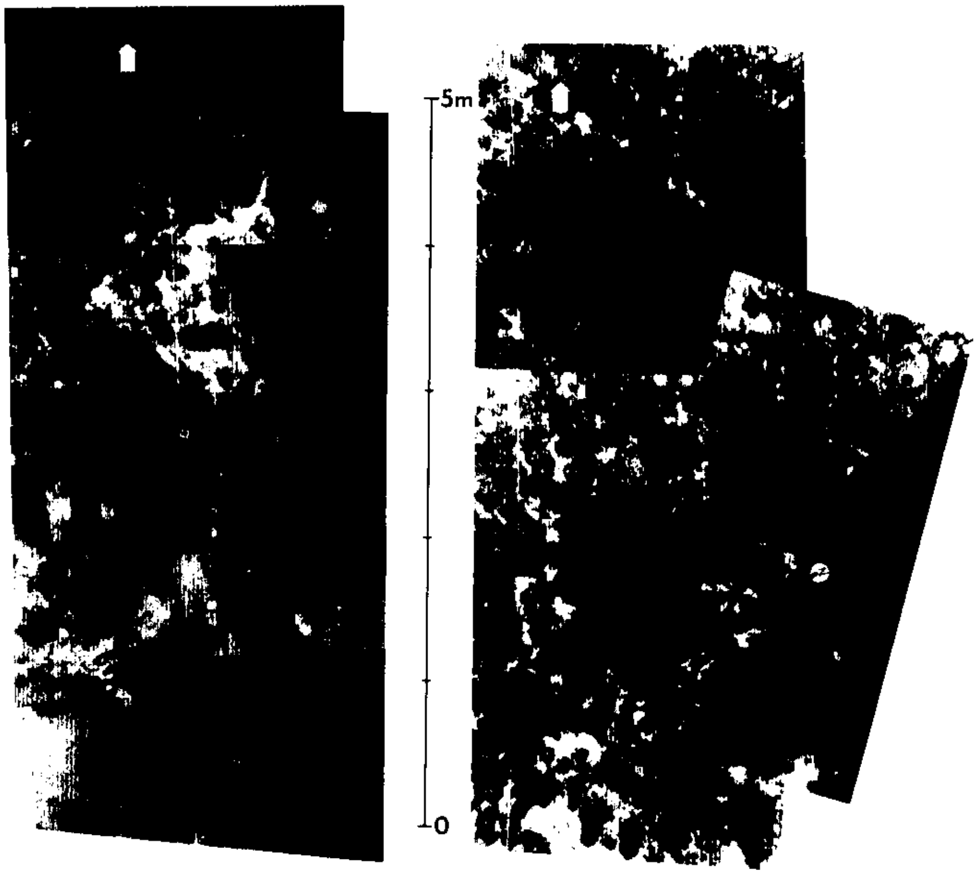

Figure 5. Photomosaics showing impacted reef area 5 m west of wellheads at left, and undisturbed coral cover 80 m north of wellheads on right. Nylon lines mark transect axis. White coded plastic float at right enables relocation of cored head corals. Note metallic debris, cables, pipe, and other debris in impact area. Arrows point away from drilling site.

In spite of the greatly reduced numbers of corals in the immediate area of the wells, specimens of *P. lutea* suitable for coring were found within 10 m of the wellheads on all but the west transect. Here, no *P. lutea* of suitable sampling size were seen closer than 62 m to the point of drilling. To test possible differences in effects of drilling on *P. lutea* at various distances from the point of drilling, growth rates of those corals sampled within a radius of 20 m around the wellheads were averaged and compared with growth averages of those corals growing at progressively greater distances from the drilling site (Table 1, Fig. 8). Results are as follows.

A trend of declining growth is indicated during a 2-year pre-drilling period (January 1977 to January 1979) in all but the most distant of Matinloc corals (80–100 m; Fig. 8). After drilling was initiated (November 1979), a resurgence, then decline, in growth is indicated in those corals from 0 to 40 m from the wellheads (Fig. 8). Growth rates of corals beyond this distance underwent a similar but reduced growth increase following drilling of Well No. 1 but showed little or no decline after the drilling of Well No. 2 (Fig. 8). Growth-rate averages for *P. lutea*

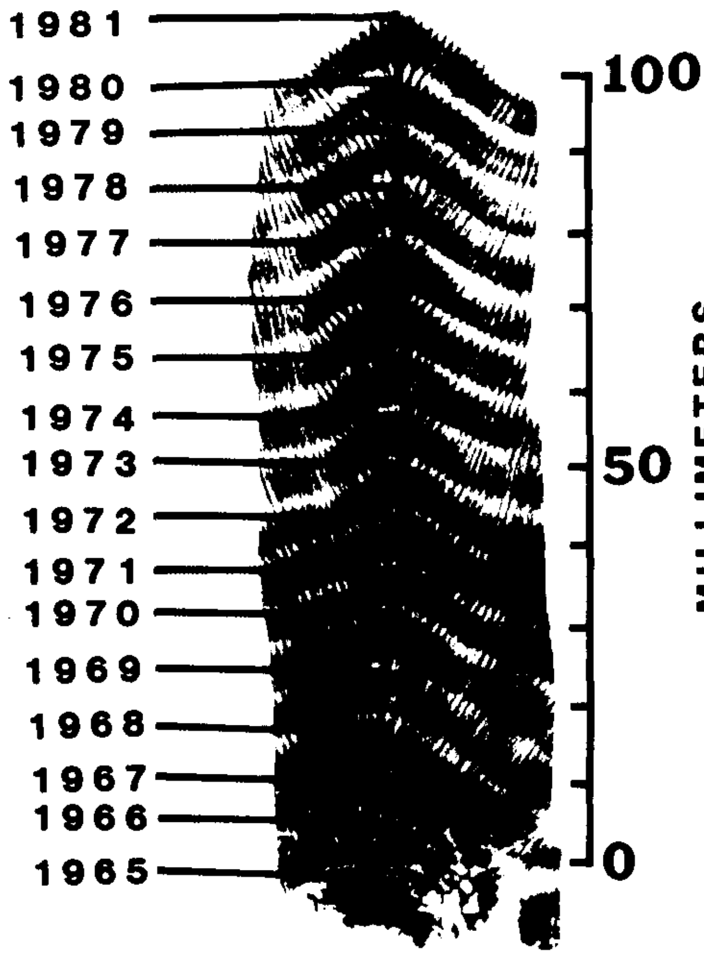

Figure 6. X-radiograph positive print of *Porites lutea* core slab from Matinloc showing annual growth bands marked along the major axis of growth. Note small amount of low-density banding within each yearly growth couplet. Highsmith (1979) recorded similar skeletal density increase with depth in Enewetak *P. lutea*.

from a control reef 1.25 km northwest of the study site indicated a periodicity of waxing and waning growth comparable to growth-rate oscillations seen in growth averages of Matinloc corals at 0–20 and 20–40 m from the wellheads (Fig. 8).

Because of the considerable variation in growth rates (standard deviation bars shown in Fig. 8), growth records of individual corals at all sampling sites were also plotted (Fig. 9). These data clearly indicate that most Matinloc and Matinloc control *P. lutea* have a long history of widely fluctuating growth rates and that with few exceptions, reductions in growth during drilling were equalled or surpassed by growth declines in pre-drilling years.

Discussion

A striking feature of coral ecology observed at both the Matinloc Field area and the control site is the small number of both massive and branching coral

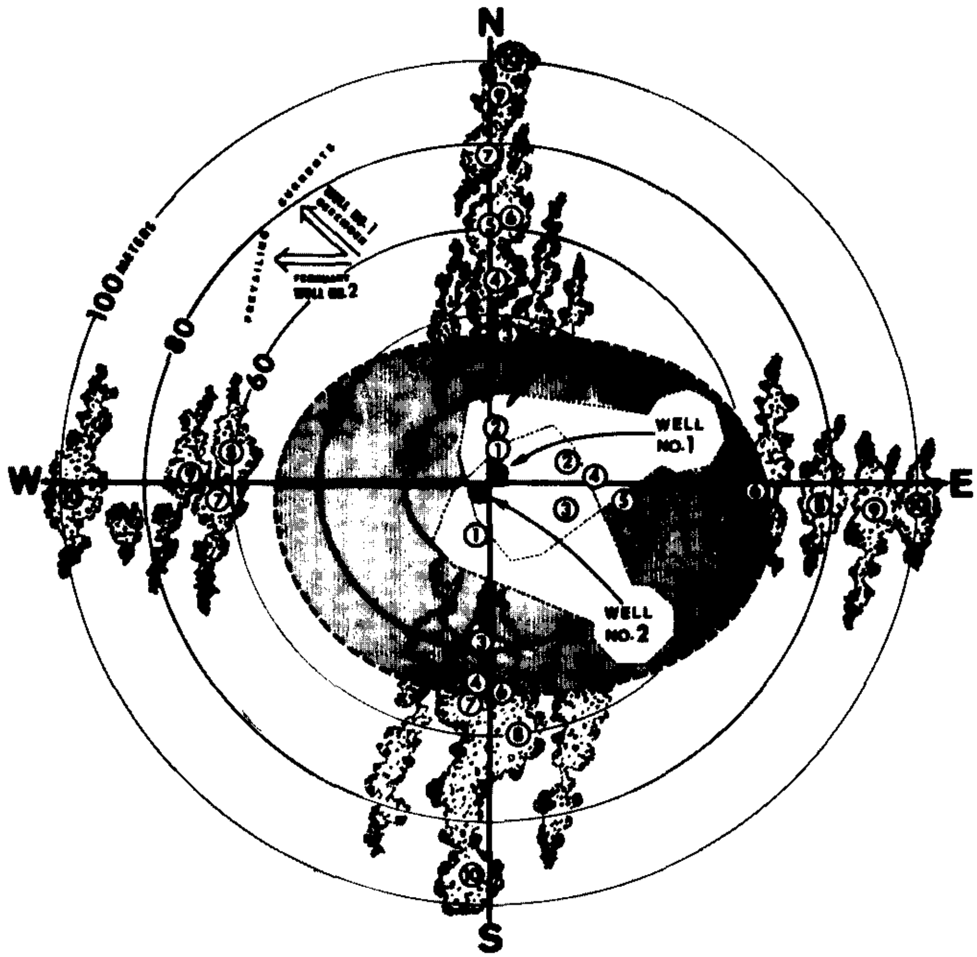

Figure 7. Plan view of Matinloc study site. Area of drilling impact is indicated by gray ellipse. Triangular outlines (drawn to scale) within impact zone indicate shape of drilling vessel and its position during drilling of each well. Small numbered circles mark location of individual *Porites lutea* cored during study (Table 1). Concentric rings indicate distance from wellheads at 20-m intervals. Shape and orientation of spur-and-groove reef formation is accurate, but size is exaggerated ×2, and reef cover in area of impact zone has been partly omitted for clarity.

colonies, either living or dead, greater than 50 cm in diameter. This feature is especially interesting with regard to dead colonies. Although scattered coral-encrusted coral boulders were observed in both areas, the extent of heavy coral growth covering them precluded their having been living at the time the wells were drilled. The fact that we observed no recently killed massive corals at the drilling site attests to their ability to survive environmental stresses that faster growing species are unable to tolerate. It is possible, however, that small specimens were overlooked or that larger ones were so encrusted with recent algal growth that they went unnoticed.

Many of the corals cored at both sites broke free from the bottom during drilling due to poor attachment of the coral to the underlying substrate. It is likely that competition for substrate attachment by faster growing species has left few niches

Table 1. Yearly growth rates by core number and transect (in mm) of individual *Porites lutea* at Matinloc and at a control reef 1.25 km northwest of Matinloc. Note that core (sample) numbers correspond to numbered circles in Figure 7, indicating core locations along transect lines. Dashes indicate no growth-rate data for years indicated

	East Transect (Matinloc)										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
1980–81		3.6	3.5	3.8	4.9	4.1		7.5	6.3	6.5	5.0	1.4
79–80		5.4	6.6	5.3	6.5	7.8		3.4	9.9	7.0	6.5	1.5
78–79		5.4	4.3	2.7	3.8	4.6		5.4	8.1	6.0	5.0	1.5
77–78		6.5	5.7	4.1	5.2	4.8		6.6	7.2	5.8	5.7	1.0
76–77		5.4	6.2	3.1	4.5	5.3		6.8	7.4	4.6	5.4	1.3
75–76		4.7	5.8	4.4	4.0	5.4		5.9	7.7	4.0	5.2	1.2
74–75		3.7	—	3.9	5.1	4.5		6.5	7.9	5.1	5.2	1.4
73–74	No Core	5.4	—	4.1	6.4	5.0	No Core	5.6	7.7	4.9	5.6	1.2
72–73		5.8	—	5.5	4.4	4.2		5.0	8.9	—	5.6	1.6
71–72		5.2	—	6.0	5.1	5.8		5.2	7.5	—	5.8	0.8
70–71		—	—	5.2	4.0	5.0		7.5	7.5	—	5.8	1.4
69–70		—	—	6.8	4.8	4.6		4.9	6.4	—	5.5	0.9
68–69		—	—	7.1	4.1	4.2		—	—	—	5.1	1.4
67–68		—	—	4.1	6.1	4.9		—	—	—	5.0	0.8
66–67		—	—	4.7	—	5.4		—	—	—	5.1	0.4
65–66		—	—	5.5	—	—		—	—	—	5.5	—
64–65		—	—	3.9	—	—		—	—	—	3.9	—
Mean growth		5.1	5.2	4.7	4.9	5.0		5.9	7.7	5.5	5.3	0.9

	West Transect (Matinloc)										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
1980–81							3.4	4.3	6.2	3.2	4.3	1.2
79–80							4.0	3.5	8.1	4.5	5.0	1.8
78–79							3.2	4.1	5.2	3.7	4.0	0.7
77–78							4.3	4.3	6.4	4.2	4.8	0.9
76–77							5.7	4.0	6.9	4.0	5.2	1.2
75–76							5.6	3.7	7.4	5.8	5.6	1.3
74–75							—	4.4	5.4	—	4.9	0.5
73–74	No Core	No Core	No Core	No Core	No Core	No Core	—	5.4	6.1	—	5.8	0.4
72–73							—	4.2	6.7	—	5.5	1.3
71–72							—	6.3	5.1	—	5.7	0.6
70–71							—	6.1	3.9	—	5.0	1.1
69–70							—	4.9	—	—	4.9	—
68–69							—	5.4	—	—	5.4	—
67–68							—	4.0	—	—	4.0	—
66–67							—	4.0	—	—	4.0	—
65–66							—	3.7	—	—	3.7	—
64–65							—	3.7	—	—	3.7	—
Mean growth							4.4	4.5	6.1	4.2	4.8	0.8

	North Transect (Matinloc)										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
1980–81	4.0	5.2	3.8	6.0	6.6	5.9	6.8		4.7	7.4	5.6	1.2
79–80	6.3	8.8	7.4	4.3	6.2	4.9	6.5		3.6	5.0	5.9	1.5
78–79	8.8	4.9	7.9	4.1	7.2	4.6	4.6		3.4	7.0	5.8	1.8
77–78	5.2	5.3	6.8	5.0	6.5	—	3.6		3.4	7.5	5.4	1.4
76–77	5.6	9.0	7.6	7.5	7.0	—	5.5		5.3	6.8	6.8	1.2
75–76	6.9	8.3	7.2	5.2	7.2	—	6.9		—	9.2	7.3	1.2
74–75	7.6	6.5	8.8	4.6	6.6	—	6.9		—	8.8	7.1	1.4
73–74	5.2	5.8	—	4.3	6.8	—	—	No Core	—	9.6	6.3	1.8
72–73	—	7.2	—	4.9	6.6	—	—		—	9.4	7.0	1.6
71–72	—	4.3	—	4.8	6.5	—	—		—	7.7	5.8	1.4

Table 1. Continued

	North Transect (Matinloc)										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
70–71	—	5.3	—	5.4	5.9	—	—		—	6.5	5.8	0.5
69–70	—	—	—	2.9	6.9	—	—		—	5.7	5.2	1.7
68–69	—	—	—	5.2	7.5	—	—		—	8.8	7.2	1.5
67–68	—	—	—	6.6	5.7	—	—		—	6.9	6.4	0.5
66–67	—	—	—	3.6	5.8	—	—		—	6.6	5.3	1.3
65–66	—	—	—	5.8	5.5	—	—		—	7.5	6.3	0.9
64–65	—	—	—	4.8	—	—	—		—	—	4.8	—
Mean growth	6.2	6.4	7.1	5.0	6.5	5.1	5.8		4.1	7.5	6.1	1.0

	South Transect (Matinloc)										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
1980–81	3.8		4.0	3.9		5.8	2.8	6.8		4.8	4.6	1.3
79–80	5.2		3.4	6.0		6.5	2.3	5.8		4.6	4.8	1.4
78–79	5.0		4.8	7.5		4.3	2.9	5.2		5.4	5.0	1.3
77–78	3.8		4.1	6.3		6.4	3.4	6.8		5.6	5.2	1.3
76–77	4.3		5.0	9.6		6.9	3.7	7.5		5.2	6.0	1.9
75–76	—		4.7	8.4		6.7	2.6	6.5		4.4	5.6	1.9
74–75	—	No Core	4.2	7.9	No Core	7.5	2.6	5.6	No Core	5.5	5.6	1.8
73–74	—		4.3	6.4		5.7	2.9	6.1		6.0	5.2	1.2
72–73	—		4.1	6.5		4.9	2.7	6.1		5.2	4.9	1.3
71–72	—		4.5	6.0		3.4	3.1	6.9		4.3	4.7	1.4
70–71	—		3.7	6.7		6.6	3.3	6.3		—	5.3	1.5
69–70	—		4.6	6.2		8.4	3.2	6.5		—	5.8	1.8
68–69	—		4.4	8.2		5.7	2.3	6.5		—	5.4	2.0
67–68	—		—	—		6.4	—	—		—	6.4	—
66–67	—		—	—		6.1	—	—		—	6.1	—
Mean growth	4.4		4.3	6.9		6.1	2.9	6.4		5.1	5.4	1.3

	Matinloc Control Cores										$\bar{x}$ Growth Rate	SD
Core No.	1	2	3	4	5	6	7	8	9	10		
1980–81	4.1	3.7	3.7	5.6	4.9	4.6	4.2	4.0	5.4	4.0	4.4	0.6
79–80	4.3	6.7	6.2	7.2	5.9	5.6	5.1	8.0	5.9	4.9	6.0	1.1
78–79	4.1	5.4	5.1	5.1	7.2	4.9	5.9	6.8	7.4	3.6	5.6	1.2
77–78	6.0	5.5	5.8	6.1	6.5	5.1	4.5	4.5	5.0	4.4	5.3	0.7
76–77	—	6.5	5.7	7.6	6.0	5.1	4.8	7.4	—	4.6	6.0	1.1
75–76	—	6.2	6.4	4.9	6.4	3.9	6.9	6.7	—	3.9	5.7	1.2
74–75	—	7.7	5.9	9.2	5.7	4.5	3.8	5.8	—	3.5	5.8	1.8
73–74	—	5.1	5.8	8.1	5.1	—	3.5	6.2	—	4.3	5.4	1.4
72–73	—	4.7	5.3	4.8	5.1	—	6.6	—	—	4.3	5.1	0.7
71–72	—	4.0	4.6	6.6	3.8	—	6.2	—	—	3.5	4.8	1.2
70–71	—	—	3.8	6.6	4.2	—	8.3	—	—	4.9	5.6	1.7
69–70	—	—	5.1	7.4	5.3	—	9.1	—	—	3.9	6.2	1.9
68–69	—	—	3.5	—	2.4	—	9.4	—	—	5.0	5.1	2.7
67–68	—	—	4.0	—	5.0	—	8.4	—	—	4.3	5.4	1.8
66–67	—	—	5.4	—	—	—	9.9	—	—	4.3	6.5	2.4
65–66	—	—	—	—	—	—	7.7	—	—	3.7	5.7	—
64–65	—	—	—	—	—	—	9.2	—	—	—	9.2	—
Mean growth	4.6	5.6	5.1	6.6	5.3	4.8	6.7	6.2	5.9	4.2	5.8	0.9

for firm attachment by the slower growing head corals, such as *Porites* sp. This, coupled with the regular occurrence of typhoons (Palawan Island is in the typhoon belt), leaves larger corals vulnerable to being overturned by storm surge. Large table coral, *Acropora* sp., presumably would meet a similar fate because of their delicate construction, large surface area, and relatively small attachment base.

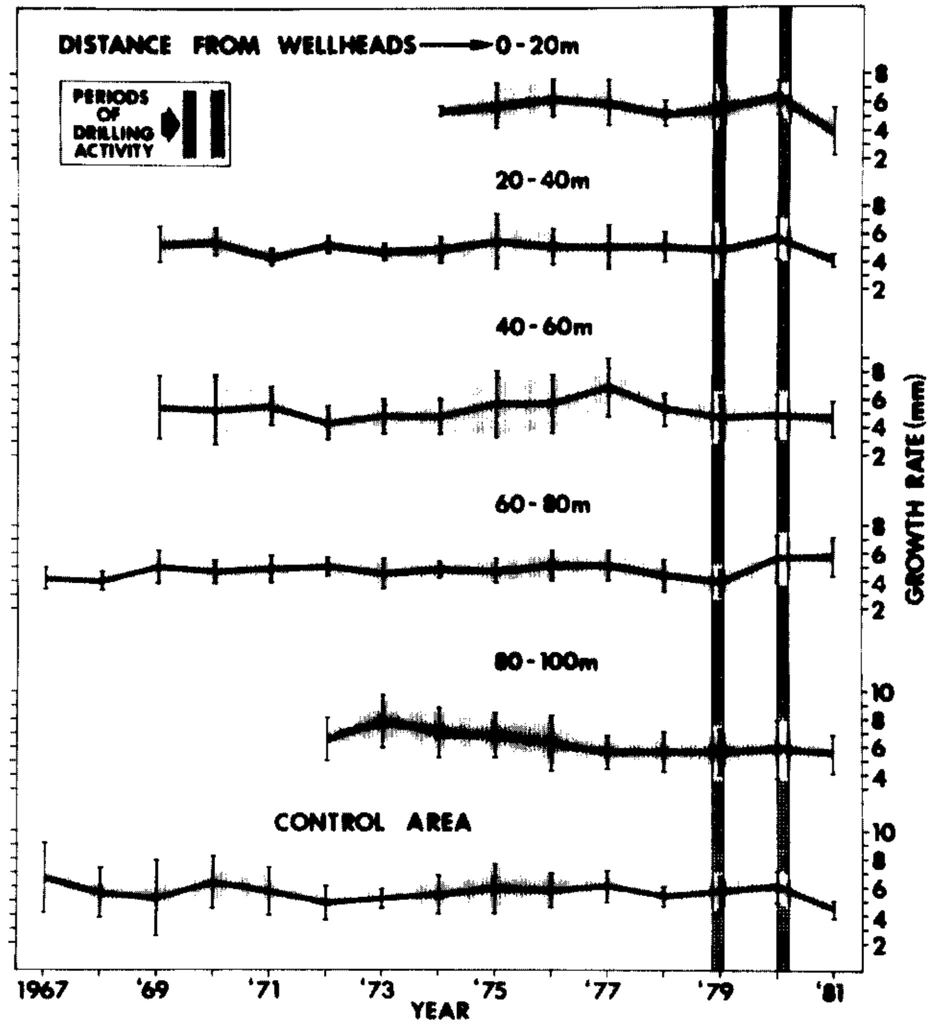

Figure 8. Growth history graphs of *Porites lutea* from Matinloc and a control reef 1.25 km northwest of the study area. Shading indicates standard deviation at the 68% confidence level.

Similar observations of scarcity of large head corals was made by Highsmith (1979) at Enewetak Atoll and by Dollar (1981) off the Kona coast in Hawaii. According to Dollar (1981), massive mortality caused by severe storms returns the entire coral community to early successional stages.

Although wind data (Fig. 3) show that the predominant direction is from the northeast and southwest, we believe that the north-northeast (approximately 10° from magnetic north) alignment of the spur-and-groove system (Fig. 7) provides a more reliable indicator of effective current direction. It was assumed, therefore, that drill-mud plumes and cuttings would impact either north-northeast or south-southwest. Thus, the north and south transects would show the maximum effect on the coral community. Surprisingly, the zone of maximum impact, as shown in Figure 7, forms an east–west-oriented ellipse. Choi (1982), who examined the effects of drill mud on cryptic reef fauna, also found an east–west-oriented ellipse of

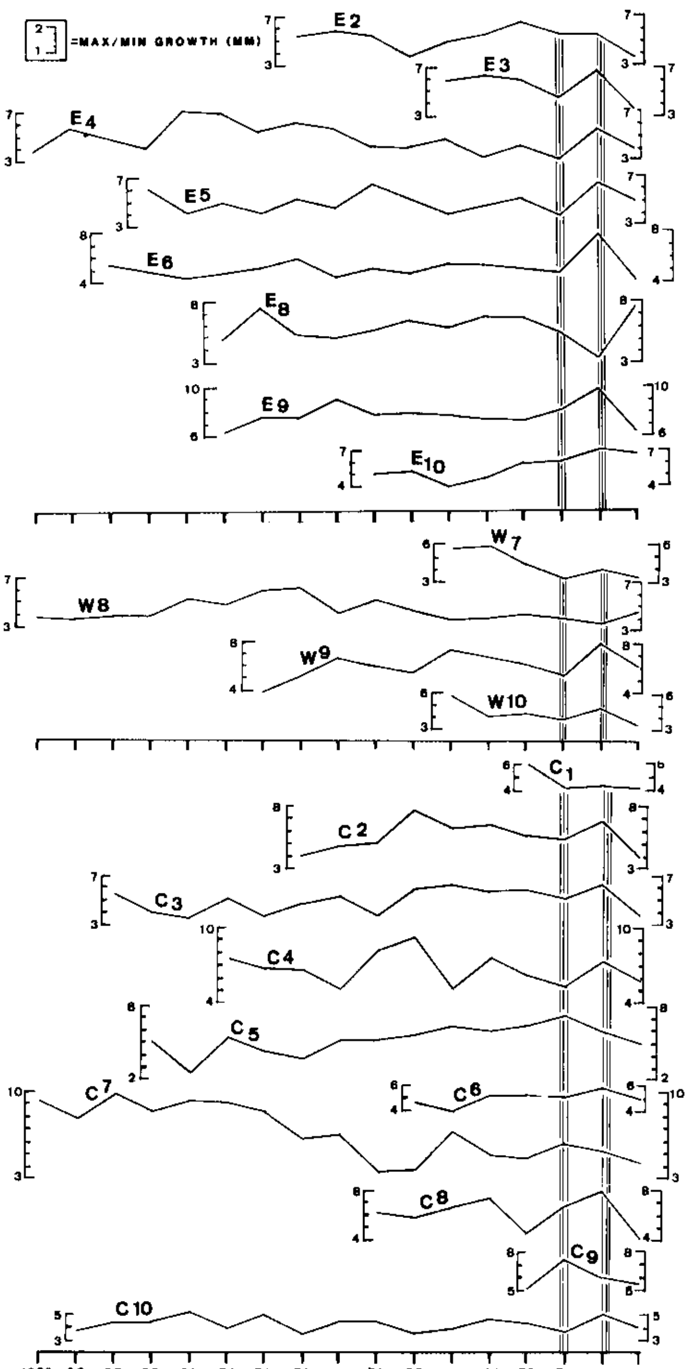

Figure 9. Growth history graphs of individual *Porites lutea* from Matinloc and a control reef. Letter/number code on graphs indicates Matinloc transects (N, S, E, W) and control reef (c). Vertical bars at years 1979–1980 indicate periods of drilling.

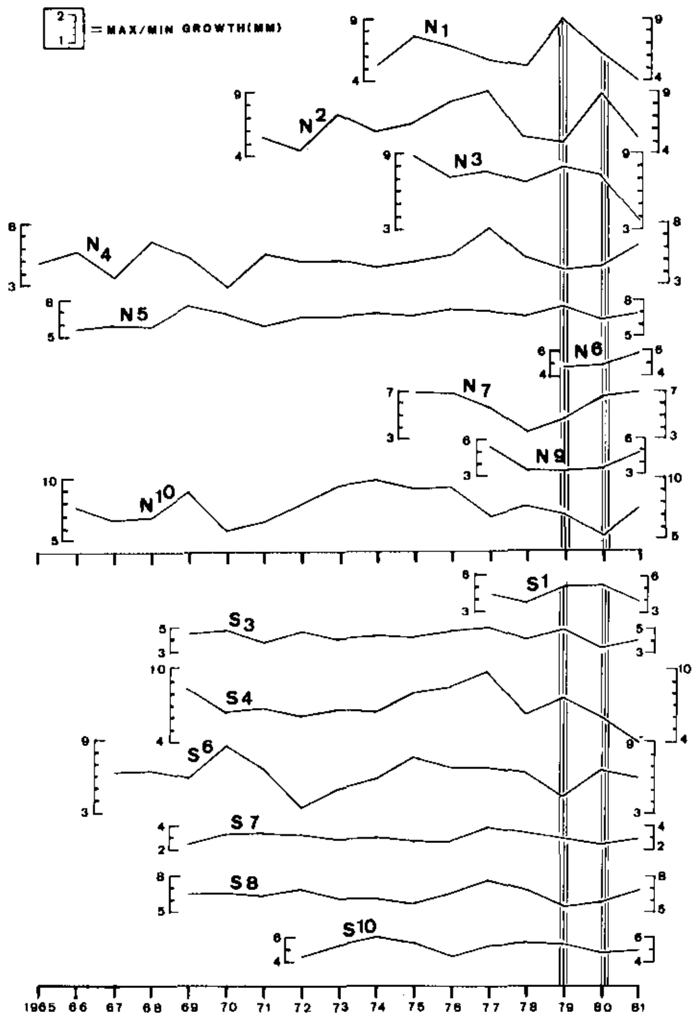

Figure 9 continued. See caption facing page.

impacted bottom. Examination of records provided by Philippine-Cities Service showed that during both periods of drilling, winds and prevailing currents had a strong westerly component (away from Palawan Island). The actual current direction during drilling is indicated in Figure 7, as is the outline of the 60-m-long jack-up drill ship. Note that the position of the drill ship was changed when the second well was drilled (Fig. 7). We therefore believe that either current direction or position of the drill ship, or both, explains why the most impacted zone trends east–west. It should be pointed out that control for the west edge of the impacted zone is poor. Suitable *Porites lutea* could not be located closer than 62 m from the wellheads on the west transect, although other species suitable for coring (Fig. 4) were living within 10 m of the wells. The main reason many corals were absent from this zone is because of chain scour. The effects of chain scour are discussed later in this report.

Samples of skeletal elements from those *P. lutea* growing closest to the wellheads were analyzed for barium (a weighing additive used in most drilling muds) using an optical emission spectrograph with the following results: skeletal material deposited prior to drilling (1975–1977) had the same amount (<100 ppm) of residual barium as that laid down during drilling (1978–1980).

Drill-mud accumulation was not detected in bottom sediments, although it was found in reef interstices (Choi, 1982). Bottom sediment was found to be very coarse and ranged in grain size from coarse sand to pebbles. Wave or water currents are often strong, a fact indicated not only by grain size but also by 10- to 20-cm-high ripples oriented perpendicular to the sediment-filled grooves (Fig. 2). Waves of 3-m height are common during the monsoon season. Thus, it seems unlikely that fine-grained drilling mud could permanently settle on living corals. Such high-energy conditions, however, would not preclude trapping of mud within the quiet reef cavities that, in effect, serve as sediment traps.

One of the more surprising observations was the absence of a cuttings pile. The drilling of a 3,000-m well could produce up to 2,100 barrels of cuttings weighing approximately 920 tons. Because both wells were drilled to a depth of approximately 2,000 m, we expected to find a pile composed of between 2,000 and 3,000 barrels of cuttings. We found, however, that cuttings were restricted to sediment-filled depressions and only within 10 m of the wells. A typhoon that struck in the interval between the drilling of Wells 1 and 2 and large waves that occurred during the monsoon season following the drilling of Well No. 2 are thought to have scattered the cuttings. The lack of cuttings in sediment samples collected at the end of each 100-m transect suggests that they were dispersed over a very wide area. It should be noted that grain size of the rippled sediment in the groove system is approximately the same as the cuttings. Therefore, because the natural sediment is frequently transported, as evidenced by ripples (Fig. 2), it seems likely that cuttings were also transported. We suspect, nevertheless, that sometime during and shortly after the drilling, a cuttings pile did exist. Zingula (1975) showed that drilling of a 3,360-m-deep well in the Gulf of Mexico produced a cuttings pile 1 m high at the center and approximately 50 m in diameter. Because of the current direction during drilling of Wells 1 and 2 at Matinloc, a temporary pile probably was formed with its longest dimension oriented east–west. Such an orientation might explain why both we and Choi (1982) mapped an east–west-trending impact zone.

Although numerous species of corals are known to be capable of recovering from considerable amounts of both manmade and natural sedimentation (Bak, 1978; Thompson, 1978; Dodge et al., 1974), it is unlikely that even sediment tolerant species would survive complete burial for more than 72 h. This estimate is based on the work of Thompson (1978), who tested effects of sediment burial on various species of Atlantic reef corals, including foliose (*Agaricia*), branching (*Acropora*), and massive (*Porites*) forms.

As noted earlier, the hard-coral community at Matinloc is dominated by foliose, branching, and plate-like forms, most of which are less than 15 cm in height. It is therefore likely that death of these low-profile corals within the drilling impact zone (Fig. 7) was due to smothering by a prolonged and localized buildup of cuttings. The fact that some of the corals within the zone of impact survived (primarily elevated head corals) suggests a low level of cuttings deposition and/or a constant partial removal of sediment accumulations by bottom currents.

A highly visible feature of the impact zone was a rusty brown stain that covered much of the rocky surfaces and sediments. This area of discoloration closely approximated that of reduced coral cover. We first concluded that staining resulted from corrosion of iron debris, such as cables and pieces of casing and grating that littered the sea bottom near the wells in the south transect (Fig. 5).

As noted by Choi (1982), closer examination revealed that much of the staining probably originated as pipe scale contained within the cuttings. One of us (EAS), who has examined well cuttings, estimates that pipe scale makes up between 1 and 2% of most drill cuttings. At times, especially following a "trip" (when the entire drill string is removed to replace a worn bit) or when the well requires extensive use of casing, the percentage of pipe scale can increase dramatically. We therefore believe that most of the staining noted was due to pipe scale in a cuttings pile subsequently dispersed by storms and strong currents. It should be noted, however, that similar staining is commonly present around shipwrecks and lighthouses in reef areas. Whether oxidized iron is significantly toxic to be lethal to corals or inhibits their growth is not known.

Growth rate fluctuations in Matinloc *P. lutea* could be affected by seasonal changes resulting in prolonged cloudiness which would reduce light levels. In addition to causing turbidity that would reduce light penetration, typhoons are also commonly preceded by cloudiness that persists even after passage of the storm. Another possible cause is atmospheric haze, either from fires (slash-and-burn agriculture is still used in the area) or volcanic activity. The area is known for spectacular sunsets resulting from volcanic ash.

An additional factor that may have affected coral growth and survival is shade. The 60-m-long drill ship (see Fig. 7 for ship outline and positions) covered most of the east transect for a total of approximately 6 months. Hermatypic corals growing at a depth of 26 m are near their depth limit because of reduced light. Therefore, it seems likely that shade cast by a large drill ship would have a significant effect. (Shade probably explains the lack of live coral beneath a 100-year-old lighthouse along the Florida reef tract; personal observations.) Evidence in support of shade-induced growth reduction by natural means is well illustrated in Figure 5, where an *Acropora* sp. table coral can be seen encroaching over a small head coral, *Cyphastrea* sp. Although this coral was cored, its growth bands, as mentioned earlier, were too diffuse to measure. Periodic removal of weakly attached, fast-growing species, such as this table coral, by typhoons would permit a return to normal growth conditions.

Of all the effects observed, the most destructive was caused by an anchor chain. A zone extending approximately 30 m to the northwest and west had been completely scoured by the anchor chain that holds the wellhead marker buoy in position. We suspect that the dead area on the coral in Figure 4 was caused by chain scour, and even though the seas were calm during our study, we observed and filmed reef rubble being moved by the heaving anchor chain. The anchor chain undoubtedly had considerable effect on the northwest part of the shaded impact zone shown in Figure 7. We feel that such damage could be avoided by using a positively buoyant synthetic rope, such as polypropylene, secured to a short chafing chain at the anchor. A subsurface float would maintain the chain above the sea-floor if rope flotation were insufficient to raise it. Davis (1977) reported similar damage from anchor chains to *Acropora cervicornis* reefs in Florida.

Thompson and Bright (1980) showed in bioassay experiments with seven species of coral that concentrations of about 500 ppm suspended solids were required to kill three of the species in a 96-h test. At 150 ppm, none of the corals were killed, although there were marked behavioral effects, and at the lowest concentration, approximately 50 ppm, none were killed and only the most sensitive species showed behavioral effects, such as polyp retraction and mucous production.

A later study of the concentration of suspended solids in the plumes of seven different exploratory drilling rigs in the Gulf of Mexico (Shinn et al., 1981) suggested that the concentrations tested by Thompson and Bright (1980) were unrealistically high. In the plume study, suspended solids were found to be diluted to less than 10 ppm 24 m from the discharge pipe (Shinn et al., 1981), and at 100 m from the pipe, concentrations were so near background levels that they could not be measured, even though the plume was still visible.

Using drill mud from a land-based drilling operation, Szmant-Froelich et al. (1981) performed a 6-week-long physiological study of *Montastraea annularis* in the laboratory, using 0-, 1-, 10-, and 100-ppm concentrations. The 100-ppm concentration had a pronounced deleterious effect on respiration, photosynthesis, calcification, and NH_4 and NO_3 uptake. The 10-ppm and 1-ppm concentrations had little effect when compared with controls; however, the feeding response of the corals was noticeably affected. Muds legally allowed in the offshore environment are probably less toxic than the onshore mud tested by Szmant-Froelich et al. (1981).

Grigg and Dollar (1981) demonstrated that mud- and clay-size material do not accumulate in a true reef area. They described the grounding of a cargo ship on French Frigate Shoals, a National Wildlife Refuge in the Hawaiian Islands, in which 2,200 tons of kaolin cargo was jettisoned directly on the reef. Kaolin is similar to montmorillonite, a highly absorbent clay mineral that is often used as a major ingredient of drilling mud, and the amount dumped would have made enough drilling mud to drill several 3,000-m-deep oil wells. Surveys conducted 2 weeks after the spill revealed that the only significant damage was a 2- to 3-m-deep impact channel cut into the reef by the ship's keel. Corals and other marine life were unaffected outside a 50-m radius of the impact zone.

With all these observations in mind, we believe that drilling mud, when compared with other aspects of drilling, constitutes a minor threat to coral growth under the environmental conditions described here.

It should be noted, however, that once commercial quantities of oil or gas are located, a permanent production platform is then installed for the drilling of additional wells and for maintaining production. The shade from such a permanent platform will seriously impede coral growth, and indeed coral growth is practically non-existent beneath lighthouses constructed on coral reefs in Florida. As we observed at nearby Nido oil field, however, corals will and do grow on the sunlit parts of platforms; thus, although coral growth will probably cease on the seabed directly beneath the platform, an equal amount of biomass might become established on the structure itself.

Metallic debris, such as observed in this study, has an immediate impact where it lands, and such dumping should be discouraged. This material will in time, however, be overgrown and become a part of the reef, as do shipwrecks and the debris discarded from lighthouses. How quickly and where denuded coral areas at Matinloc will become recolonized to their previous density levels will depend, in part, on the size and placement of the production platform, which at this writing is being prepared for installation at the site.

Conclusions

Live-coral cover at Matinloc, consisting of foliose, branching, and plate-like forms, was reduced 70 to 90% around the wellheads in an elliptical impact area that extended 35 m north, 50 m south, 65 m east, and 50 m west. In addition, a distinct rust-stained area of bottom sediments and reef rubble was found to coincide with the zone of reduced coral cover; however, it is not known if iron staining contributed to coral mortality. Corals outside the drilling impact zone were comparable to those at a control reef 1.25 km away.

Drill mud did not accumulate in bottom sediments, although it was found in cavities of reef rubble by Choi (1982). Matinloc *Porites lutea* skeletal elements that were deposited during pre-drilling and drilling years both contained less than 100 ppm residual barium. No trace of a cuttings pile was found at the drill site, and well cuttings were only found in bottom sediments within 20 m of the wellheads.

Growth-rate data from *P. lutea* collected at both Matinloc and a control reef indicate that widely fluctuating growth rates throughout the growth history of most of these corals masked any appreciable reduction in growth that may have been caused by drilling. The most severe observable damage to the coral community was caused by an anchor chain; however, since reduced live-coral cover extended well beyond the range of the anchor chain, burial and subsequent smothering of corals by a cuttings pile which is no longer present probably had an even greater impact.

Acknowledgments

The authors gratefully acknowledge assistance of the following persons: J. W. Collins, J. C. Quigel, and K. J. Schaudt of Cities Service Company for their considerable logistical and technical services before, during, and after the study; the captains and crews of the vessels J. E. WARREN and PALEX SERVICE for their untiring efforts to make our at-sea operations a success; I. Macintyre for his aid during drilling and for identification of corals; D. R. Choi for his help during drilling; L. Kump for processing core samples; and C. Sherrer for aid in assembling photomosaics. Special thanks are extended to E. D. Gomez and J. W. McManus of the University of the Philippines for their encouragement and information concerning Philippine coral ecology. S. Earley documented the study with underwater photography. B. Lidz critically reviewed the manuscript, aided in assembling the photomosaics, and offered many helpful suggestions. J. H. Hudson, Jr. devised a simplified computer program for standard deviation calculations.

This research was supported in part by the Research and Development Program for Outer Continental Shelf Oil and Gas Operations, U.S. Geological Survey Conservation Division (now Minerals Management Service).

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DATE ACCEPTED: June 8, 1982.

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