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Internal Structure and Origin of the Double Reefs of North Bohol and the Olango Reef Flat (Philippines)

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ABSTRACT

Nine holes were drilled with a submersible hydraulic drill into the slopes and reef flats of the Cauhyan and Calituban reefs as well as of Olango Flat. The maximum depth of core penetration was 11 m. ^{14}C ages showed that the Caubyan and Calituban reefs were formed within the last 6,000 years. Corals settled on a pre-existing relief parallel to the island of Bohol, building a framework for other carbonate-producing organisms. The reef flat south of Olango has a different structure. Formation took place during a Pleistocene high sea level, e.g. 125,000 years ago.

INTRODUCTION

Parallel to the north coast of Bohol two barrier reefs, separated by a lagoon up to 30 m deep, have developed (Fig. 1). In the literature this reef type is known as a double barrier reef (Pichon 1977). The outer barrier reef, the Caubyan reef, is composed of several large units while the inner barrier is less continuous and only in the central part does it have a single large unit, the Calituban reef. The central units of these reefs are covered by no more than 1.5 m of water with large areas exposed at low spring tide. As the Camotes Sea is surrounded by islands which control wave action of oceanic origin the double reef must have developed in a rather low energy environment. Only tidal currents should be of major importance for the distribution and growth of the organisms and the distribution of the sediment.

Pichon (1977), when discussing the origin of the double barrier reef, assumes that the outer reef has first developed as a single reef similar to other tropical shorelines. For the subsequent development of the inner barrier, Pichon (1977) discusses two hypotheses: 1) longitudinal currents,

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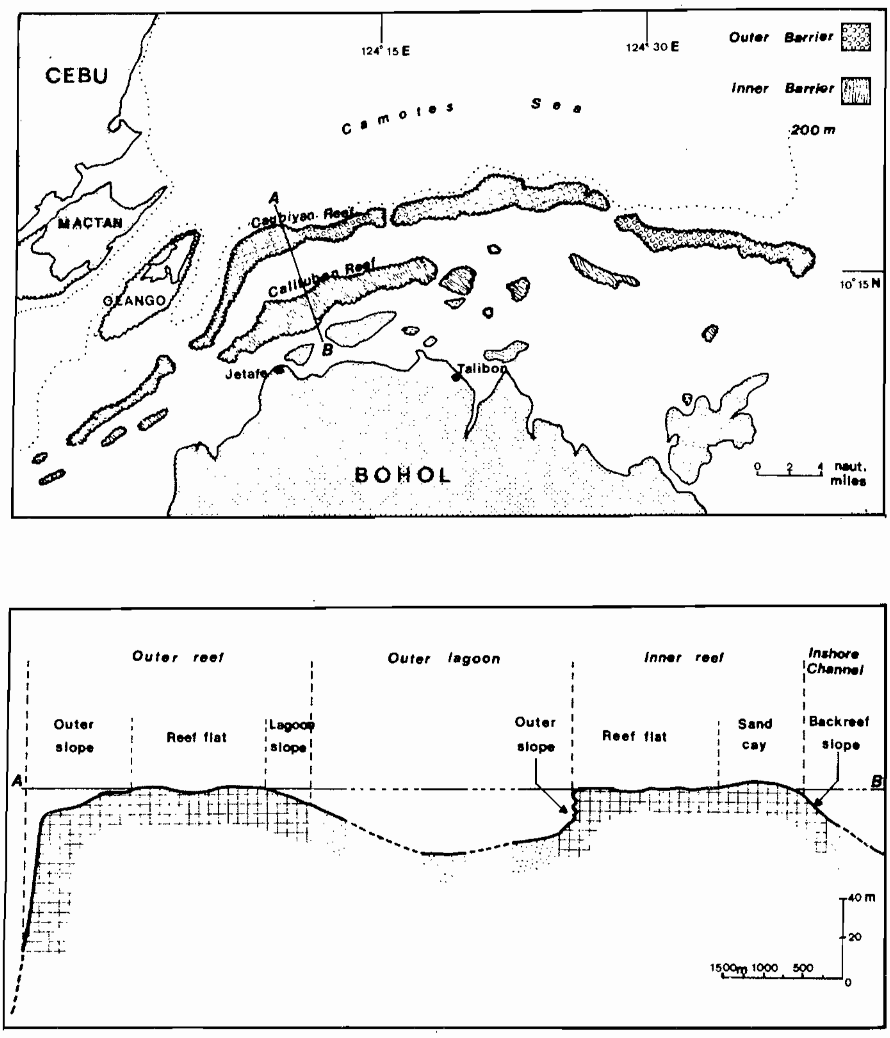

Fig. 1. Location and profile of the double barrier reef of north Bohol (after Pichon 1977).

parallel to the outer barrier, increase coral growth leading to the formation of an inner barrier; 2) the inner barrier results from a resumption of the subsidence, which previously led to the formation of the outer barrier. In the latter case the fringing reef was isolated from the shoreline and became the inner barrier. Pichon (1977) took both explanations into account but left the exact mechanisms of its formation unresolved.

For paleoclimatological studies we drilled 25 holes into coral heads and the reefs located off Mactan, and into the slopes and reef flats of the Caubyan and Calituban reefs as well as of Olango Flat. Results from six drills made in Caubyan and Calituban reefs are shown here. For comparison, data from three cores drilled into the outer slope and reef flat south of the island of Olango are also included. Here we describe the structure as well as the time frame of the accumulation of the uppermost 10 meters of the reefs and discuss possible mechanisms for their development. The results from material obtained from drilling into single coral heads and from horizontal drilling off the Marine Research Station of the University of San Carlos are reported elsewhere (e.g., Pätzold 1985).

METHODS

The submersible hydraulic drill used in this study is similar to the equipment described by Macintyre (1978), also used by E.A. Shinn and J.H. Hudson (United States Geological Survey, Fisher Island, Miami). The components with their specifications are given in Table 1. The basic concept in designing these drills was to connect an underwater hydraulic drill with a coring tool. The hydraulic drill is driven by a power unit installed on a small ship or a barge.

In this study a platform (oil-barrel raft) equipped with a 40-horsepower outboard engine and a 3 m high tripod was used. The core barrel was

TABLE 1. SPECIFICATIONS OF HYDRAULIC SUBMERSIBLE DRILL

Components	Specifications
Hydraulic power unit	Custom Hydraulics, gasoline powered
Hydraulic drill	Stanley Hydraulic Tools, Type DL 22
Water pump	Heavy duty trash pump
Water swivel	Hydrowerkstätten, Kiel
Coring equipment	Christensen, Celle
	C-wireline coring system, size CB

operated through a hole in the center of the barge. As a coring tool we used standard drilling equipment manufactured by Christensen, Celle, West Germany. Core barrel length is 1.5 m and the diameter of the inner split barrel is 43 mm. The coral cores were recovered with a wireline system lowered into the hole without removing the core barrel. The drill could easily be operated by one diver, but drilling to greater sediment depths required a three-man team. Despite the wireline system, drilling was relatively fast. For example, under normal conditions a 10 m hole was drilled within three hours from the platform. The maximum depth of core penetration was about 11 m. Core recovery was 100% from coral heads. In the sections between the larger coral heads only fragments of more than 3 cm length were recovered. Smaller particles were washed away during the coring process. In the laboratory the coral cores were cut twice lengthwise to obtain a 5 mm thick slice from the center of the core for growth rate (density banding) and isotopic studies. From one of the half-core lengths we selected 5 cm sections for ^{14}C age determinations. In the radiocarbon laboratory the core pieces were washed with distilled water and dried. Then they were inspected microscopically for impurities. The results are given as ''purity'' in Table 2. In some cases the corals were clean and well preserved and their natural holes were free of secondarily deposited calcite (marked by +). Of course, these samples are expected to give the most reliable radiocarbon ages. Other samples showed secondary holes caused presumably by boring organisms or dissolution, while the original holes were filled with carbonate cements (-sign), and the rest showed only moderate impurities (indicated by ±). We tried to remove the coarse impurities mechanically, as there is no chemical method like that for organic carbon to reliably separate the secondary material from the original sample.

Therefore, in most cases, the carbonate as a whole was converted into CO_2 gas with the addition of 10% hydrochloric acid. Afterwards the gas was purified with active charcoal and stored for at least 3 weeks to allow the decay of Radon 222 (half-life 3.8 days). Finally the radiocarbon content of the sample was measured for 2 or 3 days with a proportional counter.

From the purified gas a sample was taken for mass spectrometric measuring of the abundance ratio $R = \frac{^{13}C}{^{12}C}$ of the stable carbon isotopes.

Usually this ratio is stated as relative difference to an international limestone standard:

$$^{13}C\,[\text{‰}] = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000$$

TABLE 2. RADIOCARBON AGES AND STABLE CARBON ISOTOPE RATIO FOR REEF CORALS OFF BOHOL.

Lab. No.	Core No.	Depth cm	Purity	$\delta^{13}C$ ‰	Conv. ^{14}C Age BP ± 1 δ Corr. for -25 ‰	Milieu Corr. Age BP
KI-1931.021	XVII	150-165		-0.69	4640 ± 65	4240
.011		ca. 400		-1.03	4780 ± 100	4380
.221		ca. 490			5250 ± 55	4850
.511		590-600		-0.60	5410 ± 70	5010
.811		ca. 700		- 0.37	4940 ± 100	4540
KI-2019.011	XVIII	250		-2.10	2440 ± 65	2040
.021		ca. 400		+ 0.42	3100 ± 90	2700
KI-1932.021		310		+ 1.02	3200 ± 55	2800
.131		430-450	±	-0.90	3880 ± 90	3480
.181		630-650	+	-1.39	4450 ± 60	4050
.281		842-850			5320 ± 60	4920
KI-1970.031	XX	ca. 970	+	-1.59	2800 ± 70	2400
.131		ca. 1090	-	-3.48	3140 ± 70	2740
KI-1944.021	XXI	0-190			1950 ± 65	1550
.061		190-340	+	-1.86	3020 ± 44	2620
.071		350-500	-	-0.60	5850 ± 55	5450
.121		350-500	±	-0.42	5430 ± 70	5030
KI-1945.031	XXII	300-450	-	+ 0.20	2980 ± 55	2580
.101		450-600		-1.41	2810 ± 55	2410
.111		450-600	-	+ 0.79	2530 ± 43	2130
.161		?		-1.03	3450 ± 60	3050
.321		750-900		-3.07	4210 ± 100	3810
KI-1948.021	XXV	0-150		-2.35	5670 ± 100	5270
.081		310-450	+	-2.19	6300 ± 75	5900
.151		310-450		-1.99	6520 ± 70	6120
KI-1947.061	XXIV	90-240			3720 ± 55	3320
.091		90-240	+	-1.67	4310 ± 60	3910
.101		240-360	-	-6.59	24500 ± 520	24100
.261		240-360	-	-8.33	25300 ± 570	24900
KI-1946.021	XXIII	180-260		-6.21	16660 ± 310	16260

The conventional ^{14}C age given below is calculated for $\delta\,^{13}C = -25$. If $\delta\,^{13}C$ of the sample differs from this value, the measured age is to be corrected according to

$$T_{corr} = T_{meas} + 16\,(25 + \delta\,^{13}C)$$

For corals with $\delta\,^{13}C = -2 \ldots 0$ ‰, this isotopic correction lies within the region of + 370 to 400 years.

RESULTS

Core locations are given in Fig. 2. In the block diagram it can be seen that the Bohol reefs are separated from each other and from the mainland by up to 30 m deep lagoons and that Olango is separated from the reef system and the island of Mactan by 150 to 300 m deep channels connecting the Camotes Sea with the Bohol Strait.

Descriptions of the cores showing recovered core sections with their ^{14}C ages are given in Fig. 3 and Table 2. Fig. 3 shows that only 30% of the boreholes went through solid material, corals or cemented sediment. Only for these sections, a definite depth (cf. Table 2) could be given. Otherwise the position of single coral fragments is uncertain within the length of a core (1.5 m). The $\delta^{13}C$ values in the following column are not only a measure for the isotopic effect, but also indicative of the origin of the material. Nearly all samples belong to a distribution with

$$\delta^{13}C = (-1.14 \pm 1.16)\ ‰$$

There is no significant difference between pure and contaminated corals. In contrast, the three old samples from Olango Flat have values between -6.2 and -8.3 ‰, possibly indicating terrestrial (atmospheric) influence.

The last two columns give the results of the radiocarbon measurements. The left column contains the conventional ^{14}C age (corrected for $\delta^{13}C = -25$ ‰) in years before present (BP = before A.D. 1950). Neglecting the variation of recent activity for *terrestrial* samples, this age is the best estimation for the true (astronomical) age. For material not grown in the atmosphere, however, we must consider that the recent activity of samples may differ more or less from the standard recent activity, typical for land plants. For samples from the upper layer of the ocean (for equatorial regions this reaches down to 400 or 500 m), the recent activity (normalized to $\delta^{13}C = -25$ ‰) is about 95% of the standard. Therefore, a modern marine sample would give a conventional age of 400 years, and, as can be seen, this difference also applies for older samples. For compensation, we introduce a so-called milieu index reservoir correction (Stuiver and Polach

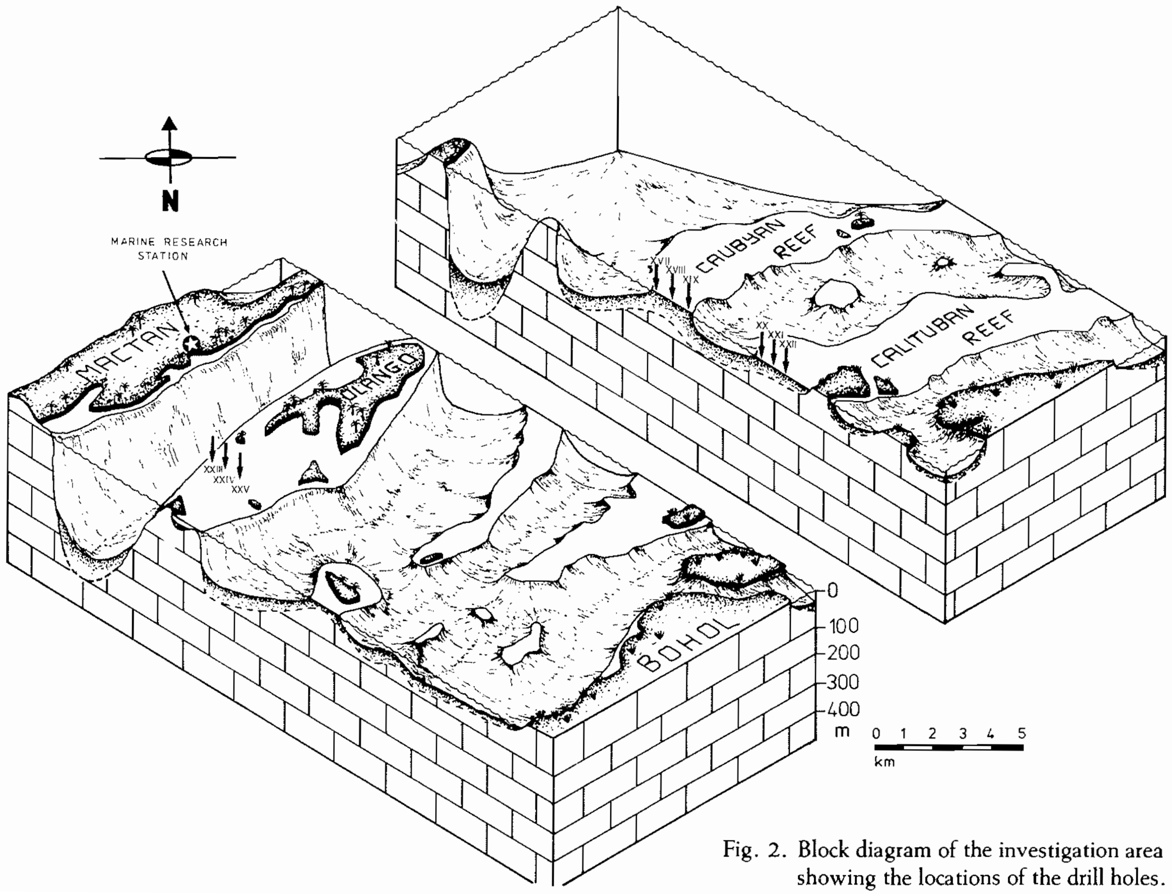

Fig. 2. Block diagram of the investigation area showing the locations of the drill holes.

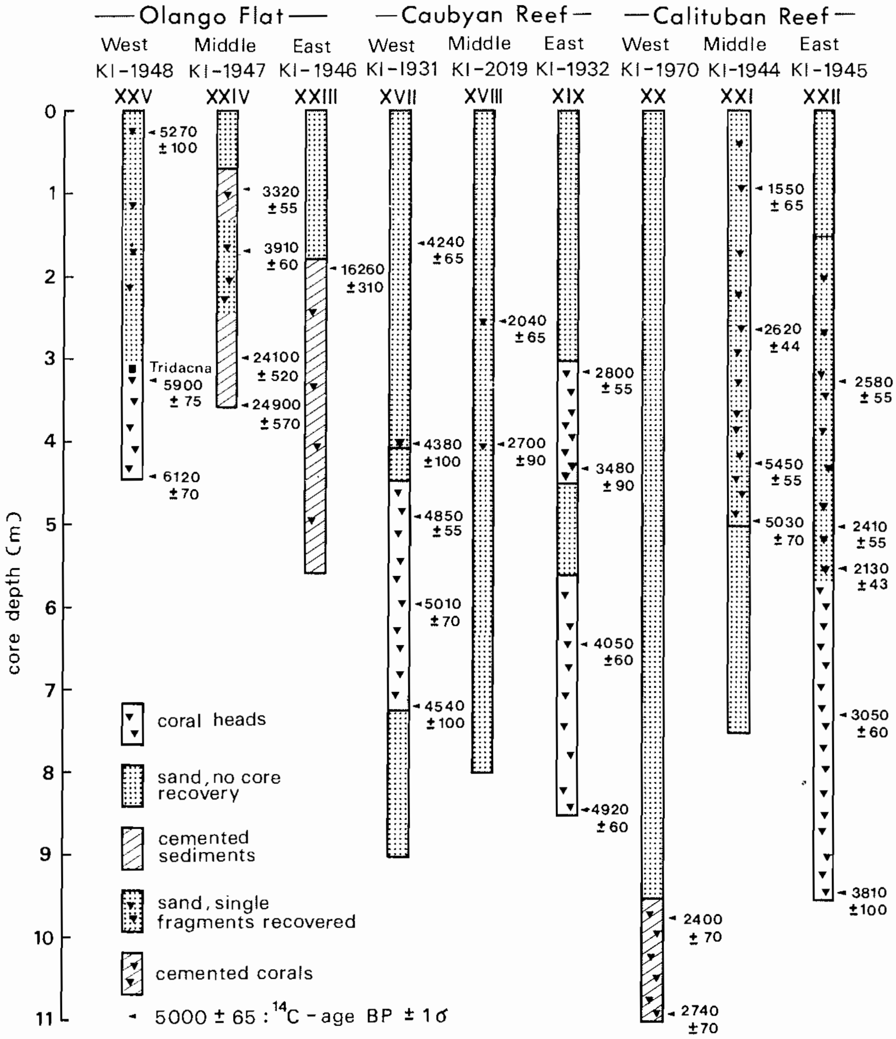

Fig. 3. Description of the drill cores showing recovered sections with their ^{14}C ages. Ages are given in years BP (before present = AD 1950) ± 1 σ and corrected for ^{13}C = -25 ‰ .

1977) subtracting 400 years from each age. The age so corrected is given as final value in the last column of Table 2 and in Fig. 3.

DOUBLE REEFS OF BOHOL

Both reefs showed nearly the same age distribution. No sample was older than 5500 years BP (3500 BC) and all but one sample were older than 2000 years BP (0 BC) (Fig. 3). From this a mean growth rate of ca. 9 m within 3500 years or ca. 0.25 cm/year followed. In particular, however, there were great differences. At present, where the coral growth is limited by the sea level at low tide, the surface of the reefs was fairly flat. But the age distribution at larger depth showed that the single coral heads were growing very irregularly producing a very rugged surface. To illustrate the situation, Fig. 4 gives a cross section through both reefs and the Olango Flat with an attempt to present the bottom surface profile as it was 4500 years ago.

OLANGO FLAT

On this flat, we found a quite different situation to that of the Bohol reefs. Only the upper meters of the cores near the Hilutangan Channel show Holocene ages ranging from 6200 to 3300 BP. The nearly coincident ages of the western hole may again indicate the former reef slope. More to the center of the flat, we found very low ^{14}C activities, which vary between 13 and 4.4% of standard recent activity. The corresponding conventional ^{14}C age was 16,000 to 25,000 years BP. But this was merely a formal age, because the sea level was at that time more than 100 m lower and the present Olango Flat lay high above the sea. Probably, these sediments were formed at earlier times beyond the range of the ^{14}C method. The small activity now found was the result of carbonate exchange with the atmosphere caused by the bicarbonate content of the rain during the Ice Age. Similarly low values (activity 7 to 10%) were found in a core drilled at the shoreline of Mactan in 0.1 to 1.2 m of water and in a beach rock piece collected on Mactan Island several meters above sea level. Dating of these rocks, of which presumably all islands between Cebu and Bohol consist, was done by Müller and von Daniels (1981). All these reef limestones belong to the "Carcar-formation" of the "Visayan-basin." A biostratigraphical subdivision of this upper Pliocene-Pleistocene sequence was difficult due to the absence of planktonic organisms (Müller and von Daniels 1981).

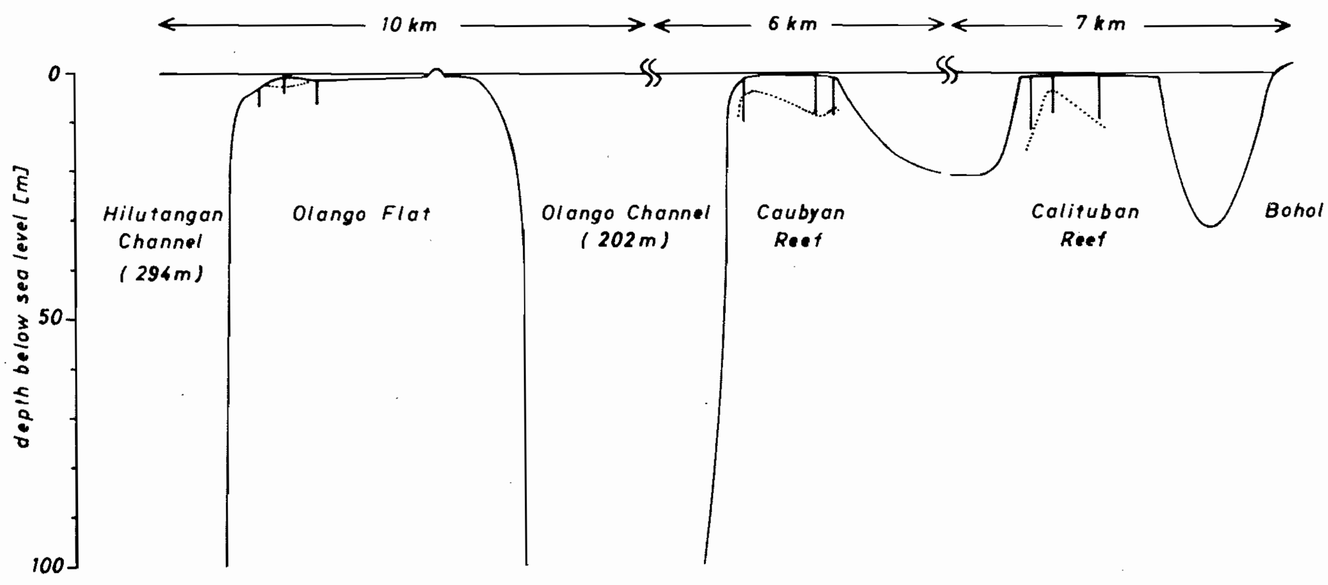

Fig. 4. Cross section through Olango Flat, Caubyan and Calituban reefs showing the expected sediment surface about 4500 years ago.

DISCUSSION

As expected with the present ecological features (Pichon 1977), cores from large coral heads were recovered on the margins of the flats while on the reef flats, only single small branching corals were found in the core barrel. In one core from the Calituban reef a large coral head was also studied. Because the uppermost ten meters of both barriers show about the same age, no indication is seen for a two step build-up of the barriers, which was one of the possibilities suggested by Pichon (1977). It is more likely that after the sea level rose to the present state about 6000 years ago, corals settled on a pre-existing relief parallel to the island of Bohol, building a framework for other carbonate-producing organisms such as mollusks, algae and foraminiferans. This pre-existing substratum is seen on some outcrops on islets situated on the flats of Caubyan and Calituban reefs. In concurrence with the postglacial sea level rise resulting from the melting of parts of the glacial polar ice caps, tectonically-caused subsidence and uplift of the basement could have influenced the build-up of the double barrier reef.

The reason why the two barriers are not connected to form a large bank area could be due to the strong tidal currents in the study area. Maassen (pers. comm.) measured current velocities of up to 60 cm/sec in the channel between the Caubyan reef and the island of Caubyan. We assume that all smaller carbonate particles produced on the flats and washed into the lagoon are transported through the small inlets between the units of the barriers into the Camotes Sea (see Werner & Wefer 1985).

The reef flat south of Olango has a structure different from the barrier reefs. In this area cemented sediments showing higher ages were recovered under a 1 to 2 m thick veneer of loose sediment. The outer slope has a structure similar to that found in the barrier reefs and was deposited at about the same time as the slopes of the barrier reefs. The formation of the flat south of Olango could have taken place during either of two time periods:

1) The sediment was produced during a former high sea level, e.g., about 125,000 years ago, and became exposed during periods of glaciation when the sea level was about 100 m lower than today. During times of exposure freshwater ran through the sediments, causing dissolution and cementation of carbonates. Cementation could have taken place until about 6000 years ago, when the area became covered with sea water. If substantial amounts of the sediments are cements deposited during the period 20,000 to 6,000 years ago then the ^{14}C-ages of 16,500 and 23,630 years BP could be the result of a mixture between the ^{14}C-activity of the Glacial/ Holocene cement and the original carbonate produced before about 40,000 years ago, showing no ^{14}C-activity.

2) The sediment was produced 16,500 and 23,600 years ago, when sea level was more than 100 m lower than today. In this case land had had to be uplifted more than 100 meters within the last 16,500 years. As no data are available showing such a strong uplift during the Holocene and as substantial amounts of cements are found within the sediment we believe that formation of the reef flat south of Olango took place during a Pleistocene high sea level stand, e.g., 125,000 or 350,000 years ago.

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