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THE CORAL REEF ECOSYSTEM AT CHIRIATAPU IN SOUTH ANDAMANS

II. CHEMICAL ECOLOGY AND SYSTEM MODEL

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ABSTRACT

The fringing reef at Chiriatapu in South Andamans is a leeward channel reef and presents a topography which ensures substantial water residence time of about 30 days. Water from the open ocean enters the reef with moderate budgets of various chemical constituents across the reef biogeochemical gradients develop in tune with the metabolic rhythm (Photosynthesis, respiration and calcification) of the biota. Organic carbon production, respiration and calcium deposition (gross and net production as inferred from carbon dioxide utilization are 4.25 and 0.56 gC $m^{-2}d^{-1}$ respectively, while the rate of calcium carbonate deposition is 1.3 g $m^{-2}d^{-1}$ by the biota alter the oxygen and carbon dioxide content, as well as the salinity, together with various ionic species to produce alternate zones of varying chemical speciation. These gradients result from the distributional pattern of the biota. The salinity differential developed between the sea and the reef initiates salt wedges, leading to circulation dynamics and exchange of water. This brings a fresh load of salt and nutrients into the reef, completing the biogeochemical cycling. The various factors controlling the circulation pattern has been considered, and a modified mathematical model has been proposed for the ecosystem. This provides a framework for the study of the various subsystem controls, and their integration into a unit system model, based on environmental parameters and coordinated Community dynamics.

INTRODUCTION

CORAL REEFS are unique systems in that they induce the biological component in the bio-geochemical cycle of the oceans and develop an ecosystem of its own, with an environment, quite distinct from the open sea. However, there is an intimate exchange between the two and the atmosphere. Each sub-system in this ecosystem is intricately related to produce a fine tuning, in order to maintain its salt and water budgets.

The metabolic activity of the biotic components of the reef system produces biogeochemical gradients along the length of the reef and this functional aspect is also co-ordinated with the structural properties of the system.

Salinity differential in small basins, coordinated with its structural aspects, together with two other factors of climatology, that is, evaporation and precipitation is well known (Sverdrup *et al.*, 1942). Such aspects of salinity differential, accelerated with calcium deposition by the components of the reef system, is exemplified in lagoonal waters of barrier reefs and atolls (Smith, 1973).

The topographical structure is such, as to slow down the in-flow, while the differential salinity creates eddies thereby, initiating a process of mixing and water exchange. The model that has been constructed for such systems, utilize this functional delay, to introduce a time residence component in the movement of water mass, in ocean basins, with differential salinity. The rate of utilization of salt and nutrients is then calculated, based on the rate of water exchange and concentration changes (Sargent and Austin, 1954; Smith and Jokiel, 1978; Hatcher and Frith, 1985).

Studies on biogeochemical gradients and nutrient cycling in coral reefs, has mainly concentrated in lagoonal environments, since atoll lagoons retain water for a relatively long time span (von Arx, 1954). Thus lagoons can provide long term, integrated records of community biogeochemical activity (Smith and Pesret, 1974). In contrast, shallow fringing reefs being rapidly flushed, the biogeochemical

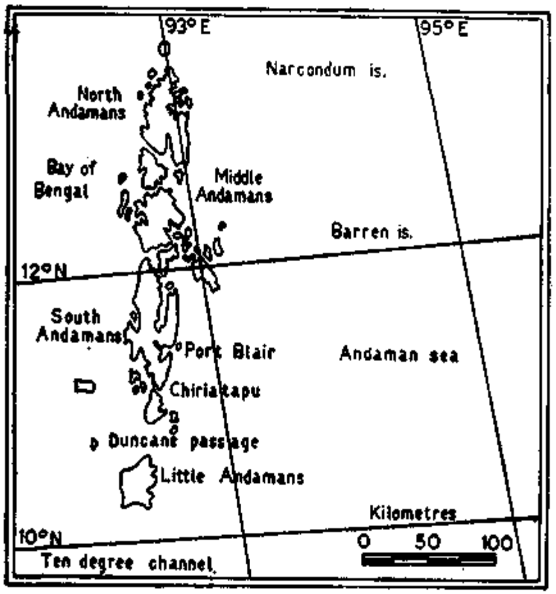

FIG. 1. Andaman Islands as well as the Chiriatapu region.

changes may be masked. However, leeward channel reefs, such as the one at Chiriatapu in South Andamans (Fig. 1), represent an intermediate condition, with respect to ecosystem function and modulation.

The Chiriatapu reef is cut off from the main ocean by an island in front (Fig. 1), which protects it from direct wave action; and limits exchange with the surrounding ocean. Water from the sea first enters the channel, and then passes over the rim of the leeward edge and across the reef.

Salinity differential and gradients in chemical constituents, due to the metabolic activity of reef organisms has been reported by Smith and Pesret (1974), Smith and Jokiel (1978), Hatcher and Frith (1985) for various reefs of the pacific. However, there is a dearth of reports on Indian Ocean reefs and that too for fringing reefs.

In this paper, we report spatial partitioning of chemical species, in relation to community distribution, and the development of a relatively stable environment in the face of a moderate advective flux. Firstly we will pulse the chemical environmental pattern and then run a mathematical model, in order to analyse the integrated system for the observed flux, with the biotic response as a function of the activity of organisms in the reef ecosystem.

Thanks are due to Dr. G. J. Bakus, University of Southern California for his constant encouragement during the course of out research work. To Dr. L. Muscatiner, University of California and Dr. J. N. Kramer, University of Southern California for discussions on respirometry and system analysis.

SITES AND METHODS

Site: The fringing reef at Chiriatapu in South Andamans (10°N and 12°N; 92° 15′E and 93°00′ E) is a small leeward channel reef (Fig. 2). The reef physiography and biota can be described in terms, of seven well defined zones (details elsewhere), but the main difference in these zones lies in the distribution of biota. The flats have a high density of biota (containing both, corals and benthic algae), while the channels are conspicuous by their absence.

were measured by a suitable mercury thermometer. Evaporation was calculated from pan measurement and compared with the formula of Jacobs (1942).

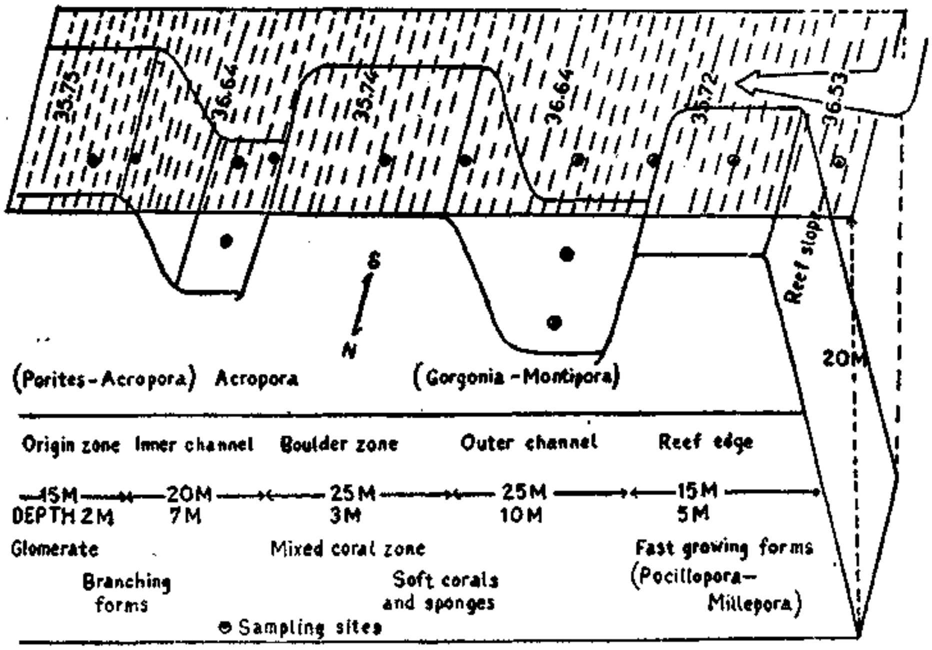

FIG. 2. Structure and zonation of the reef at Chiriatapu. The values indicate salinity isopleths, while the round markings indicate sampling sites. Arrow represents direction of water current.

Methods: Replicate water samples were collected during October-November 1979, 1982 and 1984 for each site and analysed for the chemical parameters on the spot using standard methods (Strickland and Parsons, 1968). pH was measured on a Philips PR model pH meter, while Mohr's argentometric method was used for the measurement of salinity. Midwater samples and those from depth's were collected using a suitable sampling bottle and measurements were done by the methods mentioned above. Productivity was measured using a modification of the conventional light and dark bottle method.

Transparency was measured with a standard Secchi disc, while air and water temperatures

$$E \text{ (mm/day)} = 0.14 (P_o - P_b) \ldots\ldots \text{Eq. 1}$$

Plastic cards and bottles were floated in order to determine the direction of water currents, and dye was used to monitor the movement of water mass. A tide staff graduated in metres, was placed at the low tide level, to record the tide height.

Data on pressure, clouds, relative humidity, vapour pressure, windspeed and rainfall were taken from weather charts, recorded by the Meteorological Institute of India.

Water exchange and biogeochemical flux

Conservative change: Equation 2 describes the residence time of water within the reef and is essentially a modification of that given by Svedrup *et al.* (1942) and Smith and Jokiel (1978). The equation defines the exchange of water between the reef and the ocean, with a salinity differential in a high evaporation zone. The modification in the equation implies, a situation, just opposite to the conditions in a lagoon, since the average salinity of the reef is lower than that of the ocean. The alternate salinity gradient leads to a peculiar salt wedge formation in the surface layer which checks the advective flux. The residence time (T) for the water in the reef is then given by :

$$T = \frac{Z}{E - P}\left[\frac{S_o - S_R}{S_o}\right] \quad \ldots\ldots/\text{Eq. 2}$$

Where T = mean residence time (days)
Z = mean reef depth (metres)
P = Precipitation (metres per day)
E = evaporation (metres per day)
S_R = Reef salinity (‰)
S_o = Salinity of the ocean (‰)

Non-conservative change : The biogeochemical flux due to biological processes for any material (M) within the reef with respect to residence time can then be described as :

$$\frac{\Delta M}{T}(\text{mole m}^{-2}\text{d}^{-1}) = \frac{(E\text{-}P)\,S_o}{S_o - S_R}\left[\left(\frac{M_o}{S_o}\right)S_R - M_R\right] \ldots\ldots\ldots \quad \text{Eq. 3}$$

Results

Meteorological and oceanographic setting

The average environmental conditions at the Chiriatapu reef during the period of survey are shown in Fig. 3. Atmospheric temperature in the reef varied from 27.6°C at 0700 hours to a maximum of about 32.8°C at 1300 hours, with a mean day temperature of 29.4°C. Surface water temperatures measured during the same period were 27.9 and 29.8°C respectively, with a mean value of 28.5°C. Throughout the day, the air temperature was higher than the water temperature, having a resultant effect on the rate of evaporation and consequent humidity.

Precipitation values obtained from the meteorological office averaged to about 300 cms per year. The daily average rainfall computed from weather charts, was 8 mm per day. Mean relative humidity as calculated from temperature and dew point was 74%.

Evaporation calculated from pan measurements as well as using the formula of Jacobs (1942), yielded rates of about 10.8 mm per day. The relationship between temperature, evaporation, precipitation, vapour pressure and relative humidity can be represented by a linear regression equation :

$$E - P\ (\text{metres/day}) = 0.47\,H_{IN} - 0.112 \ldots \text{Eq. 4}$$

Where H_{IN} is the hydrothermal index and is equal to :

$$T_A - T_W \times \frac{V_P}{R_H}$$

Where T_A = Air temperature (°C)
T_W = Water temperature (°C)
V_P = Vapour pressure (millibars)
R_H = Relative humidity (per cent)

Figure 3 f is a plot of these parameters, with the hydrothermal index superimposed, relative to vapour pressure. The movement of the index against E-P (Fig. 4), clearly indicates the regulation of the hydrological cycle as a purely abiotic phenomenon. It represents the evaporative power of the atmosphere, regulating the salinity as well as the flux of water.

The values obtained for evaporation and precipitation fit in well with the empirical relationship given by Wust (1935).

$$S = 34.6 + 0.0175\,(E\text{-}P) \ldots\ldots\ldots\ldots \text{Eq. 5.}$$

The calculated salinity is about 36.3‰ while the oceanic salinity at the Chiriatapu reef is

36.5‰. Equation 5 represents the modulation of salinity by the hydrological cascade system as a conservative change.

The mean depth of the reef was found to be 5.4 m. Extinction coefficient (K) varied from 0.18 to 0.20 across the reef, the higher value was metered near the shore.

At Chiriatapu the wind speed is fairly constant, 3-4 metres per second (5 knots) during ordinary conditions, but with the advent of tropical storms it may exceed the Beaufort force 4 (7 m sec^{-1}), at times it attains values of about 12-13 knots. The winds control coral growth, reef morphology, and sediment accumulation. However the reef at Chiriatapu being leeward, wind action is relatively low.

Surface water wind drift was documented by the release of drift cards. Most of the cards moved along the direction of the channel in front of the island while some of them curved round to move across the reef and towards the shore. This can be explained, if the wind it moving in a south to north direction, the E to W movement being blocked by the presence of the island in front.

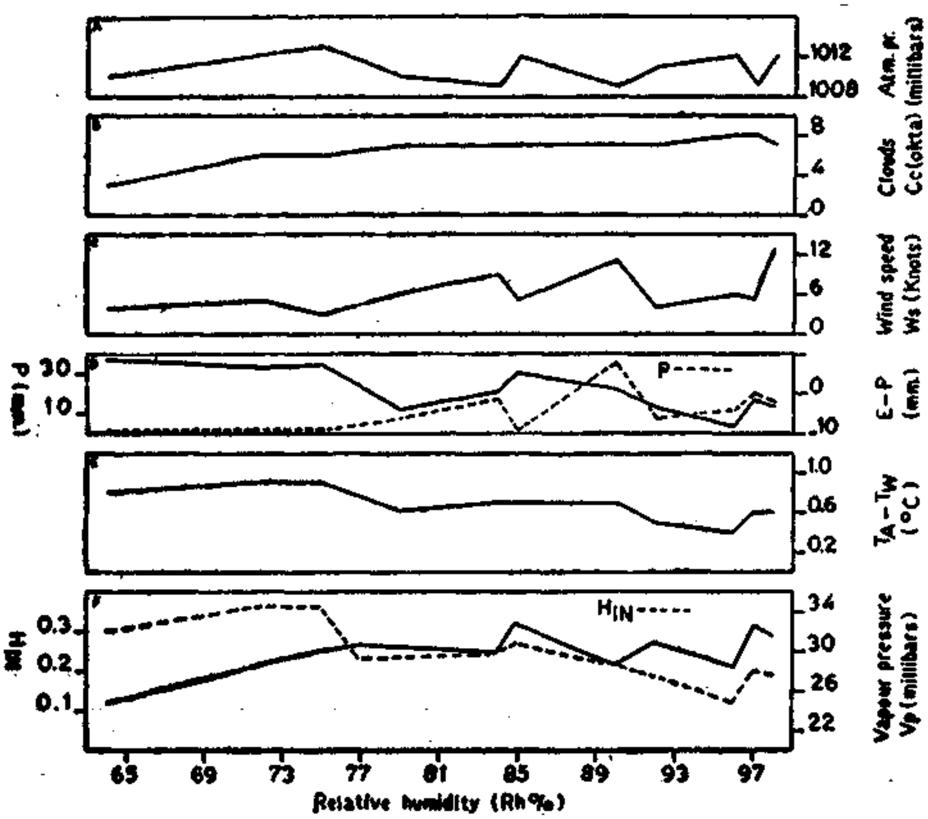

FIG. 3. Average environmental pattern at the Chiriatapu reef during the period of survey. T_A = air temperature, T_W = water temperature, E = evaporation, P = precipitation, H_{IN} = hydrothermal index and Atm.Pr = Atmospheric pressure.

Biogeochemical gradients

Salt budget: The salinity distribution in the fringing reef at Chiriatapu is shown in

Fig. 2. The most conspicuous feature is the alternate increase and decrease of salinity with respect to the various reef zones and is in sharp contrast to the linear gradient found in atoll lagoons.

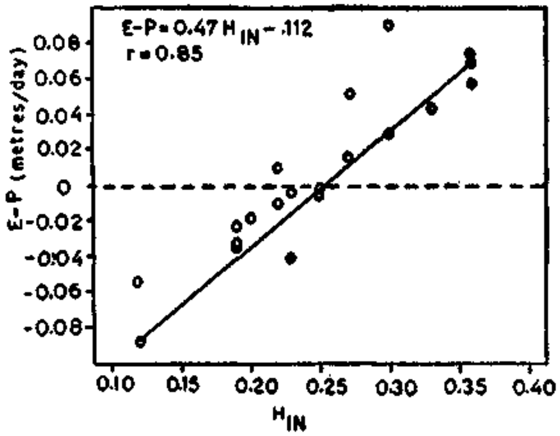

FIG. 4. Regression line of E-P versus H_{IN}.

The salinity of the ocean metered during the survey was 36.5‰ while the value fluctuated within the reef. In the zones 1, 3 and 5 where coral fauna was present, the salinity decreased to 35.8‰ whereas, in the channels (zones 2 and 4) where coral fauna was practically absent, the salinity increased to 36.6‰. By fitting the above values into equation 2, we get the mean residence time of water to be about 30 days. In the absence of ground water the major change in the salt concentration is brought about by the metabolic activity (production-respiration-calcification) of the biological component of the system and thus represents a non-conservative change.

Carbon dioxide budget

The change in the salt budget is accompanied by a change in the chemical environment, of which, the most notable, is the CO_2 system of the reef. Table 1 depicts the fluctuations, in total CO_2, alongwith its associated parameters, total alkalinity and pH. Total CO_2 showed alternate gradients with salinity and this feature is repeated by the pH, alkalinity, carbonates and bicarbonates (Table 1). The change in the total CO_2 concentration with respect to salinity can be represented by a linea regression equation as follows :—

$$CO_2\ (\text{mole/m}^3) = 0.27\ S - 7.59 \ldots\ldots \text{Eq. } 6.$$

Figure 5 is a plot of CO_2 against salinity. Total CO_2 decreased from an oceanic value of 2.376 moles/m³ to about 2.000 moles/m³ over the corals, indicating a rapid utilization or CO_2 by the biota for their metabolic activities while an increase over the channel suggests its net release.

Total alkalinity decreased from about 2.570 equiv./m³ beyond the reef to about 2.358 equiv./m³ over the corals and the change in this parameter versus salinity can be expressed by a quadratic regression equation :

$$TA\ (\text{equiv./m}^3) = -20.05 + 0.984\ S - 0.01\ S^2 \ldots\ldots \text{Eq. } 7$$

Figure 6 is a plot of total alkalinity against salinity. Since the total alkalinity bears a fairly constant relation to chlorinity, a change in the total alkalinity, effects a simultaneous change in the chlorinity. Thus a change in the total alkalinity (barring effects of precipitation and evaporation, which has been dealt earlier) is indicative of deposition or dissolution of calcium carbonate.

The utilization of CO_2 can be differentiated into three processes, production, calcification, and gas exchange and can be represented by the following expression :

$$\Delta \Sigma CO_2 = \Delta CO_2^{\,Ca} + \Delta CO_2^{\,P} + \Delta CO_2^{\,GE} \ldots\ldots \text{Eq. } 8$$

Where CO_2 = Change in total CO_2 concentration.

$\Delta CO_2^{\,Ca}$ = CO_2 flux due to calcification.

TABLE 1. *The chemical environment and its fluctuations in the fringing reef at Chiriatapu*

Zones		Salinity (‰)	pH	Total alkalinity (equiv/m^3)		Total CO_2 (mole/m^3)	
				$\frac{Mo}{So} \times SR$	MR	$\frac{Mo}{So} \times SR$	MR
6	..	36.53	7.8	2.570	2.570	2.376	2.376
5	..	35.72	8.3	2.515	2.349	2.352	1.930
4	..	36.64	7.8	2.577	2.567	2.383	2.421
3	..	35.74	8.2	2.514	2.360	2.324	2.000
2	..	36.64	7.8	2.577	2.567	2.383	2.421
1	..	35.75	8.2	2.513	2.358	2.320	2.005

ΔCO_2^{P} = CO_2 flux due to organic production.

ΔCO_2^{GE} = CO_2 flux due to gas exchange.

The change in total CO_2 and CO_2^{Ca} is calculated (Table 2) from equation 3 and alkalinity depletion respectively (for each mole of Ca CO_3 precipitated, total alkalinity is lowered by two equivalents) while organic production and gas exchange rates are inferred. Table 3 shows the utilization of carbon dioxide for the above mentioned processes. The values for gas exchange are obtained by substracting the observed value from the derived data. A positive value for gas exchange indicates evasion, while a negative value indicates invasion. From the Table it is found that the two processes organic production and calcification is quite rapid over the corals, in contrast to the channels, where there is a net release of CO_2 indicating, that respiration exceeds productivity in these zones. The CO_2 budget presented above estimates net production to be about 0.56 gC/m^2/day while the calcification rate is about 1.3 g/m^2/day (13 m moles/m^2/day).

TABLE 2. *CO_2 (m moles/m^2/day) utilization in the fringing reef at Chiriatapu*

Zones		CO_2	CO_2^{CR}	CO_2^{NP} Calculated	CO_2^{OE} Observed	
5	..	65	14	51	53	−2
4	..	−6	2	−4	−6	+2
3	..	54	13	41	43	−2
2	..	−6	2	−4	−6	+2
1	..	52	13	39	41	−2

TABLE 3. *Partitioning of the chemical energy flow through the reef ecosystem at Chiriatapu*

Zones		Gross Productivity	(gC/m^2/day) Respiration	Net Productivity	P/R
5	..	4.51	3.83	0.65	1.1
4	..	0.66	0.73	−0.07	0.9
3	..	4.30	3.77	0.53	1.1
2	..	0.66	0.73	−0.07	0.9
1	..	3.94	3.44	0.50	1.1

Partitioning of organic production

Production-respiration activity was also measured using oxygen derived data (dark and light bottle method) in order to partition the chemical energy flow through the reef ecosystem. The gross production has been differentiated to yield net production and respiration values. Table 3 shows the production-respiration data for the various reef zones. The CO_2 utilization due to production as calculated from the carbon dioxide budget shows consistency with the oxygen derived data and supports the budget of carbon dioxide presented in Table 4. The partitioning of the

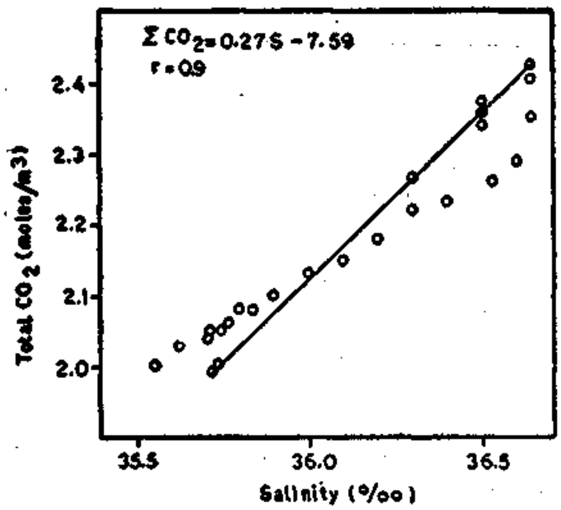

FIG. 5. Regression line of total CO_2 versus salinity.

chemical energy has been depicted in Table 5. Gross production decreased from 4.51 gC/m²/day over the corals, to about 0.66 gC/m²/day over the channels. As seen in the data presented, in the channels, respiration exceeds production and the P/R ratio decreases to about 0.9, since the coral cover and consequently the phototrophs are relatively scarce. Over the corals (zones 1, 3 and 5) however the P/R ratio increases to about 1.1, suggesting that the ecosystem is reaching its stabilized state.

Discussion

The conditions of water circulation and maintenance in the fringing ecosystem is quite complex, from that of atoll lagoons, due to a conditions advective flux. However leeward fringing reefs, like the one at Chiriatapu, represent an intermediate conditions, with a moderate residence time. The salt and nutrient budgets are modulated by a variety of factors, both biotic and abiotic, while the reef ecosystem resonates in tune through four subsystems.

Atmospheric-Ocean exchange subsystem.
Biotic-abiotic interaction subsystem.
Channel-Flat exchange subsystem.
Ocean-Reef exchange subsystem.

At Chiriatapu, the advective flux is checked, since the water enters into the reef through the channel and enables biogeochemical gradients to develop. However, a unique feature is the development of alternate chemical gradients in tune with the distribution and metabolic rhythm of the biota.

In the reef, the high temperature of the water and a constant positive difference between the sea and the air results in a high rate of evaporation as indicated by the hydrothermal index. The resultant effect is an increase in the salinity of the water in general, as a conservative change.

The carbon dioxide budget reveals, that organic carbon production is much higher in the zones where the corals are present, in comparison to the channels, which have a scarcity of benthic vegetation (Mukherjee, 1988). The high rate of primary production, with the help of the energy trappers of the first tropic level and with the calcification by corals, initiates the differentiation of the reef ecosystem from the general oceanic biome. The bulk of the organic production in the reef is provided by the benthic algae (Mukherjee, 1985) while the contribution of the phytoplankton constituents is relatively low (< 1 C/m²/day).

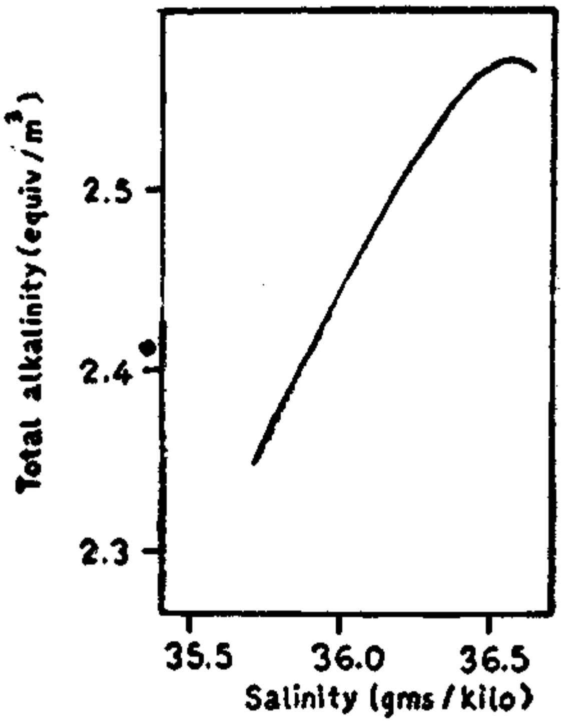

FIG. 6. Quadratic regression line of total alkalinity versus salinity.

The two way utilization of carbon dioxide triggers a chain reaction in the CO_2 system producing gradients in total alkalinity, carbonates bicarbonates and pH. Such gradients associated with the metabolic rhythm of the biota have also been reported for estuaries where salt wedges occur regularly (Dyrssen and Wedborg, 1980).

The deposition of calcium carbonate by the corals decrease the salinity in the zones 1, 3 and 5. In the channels however, the salinity is higher. The salinity differential thus produced as a non-conservative change, results in the development of alternate salt wedges. This provides an increased resistance to the movement of water, controlling to flux and providing a moderate residence time. The aging of the water stabilizes the chemical gradients thus developed and modulates, water exchange between the reef and the ocean.

The exchange process can be visualized a series of eddies functioning along the salt wedges between the coral zones and the channels replenishing salt and nutrients for the corals and completing the biogeochemical cycling.

The resultant physiography of the reef as Chiriatapu seems to be moulded by the topography of the island and modulated by envioronmental parameters such as light, temperature, precipitation and evaporation, together with wind and tidal currents. The reef in turn separates an ecosystem of its own by introducing diverse biotic components and regulates the system in tune with its metabolic rhythm.

Geological history and rate of calcification

The Chiriatapu region belongs to the serpentine group, being raised in the late cretaceous to eocene, as indicated by the nature of sediments (Srinivasan, 1978). Such raised reefs and reef associated sediments have been reported earlier in the Indian Ocean (Kuenen, 1950). As pointed out by Stoddart (1973), the last glacial low sea level reached 120 metres at 15,000 yrs B.P., and the sea then rose fairly rapidly to -20 metres at about 7,000 yrs B.P., so there is a negative shift of sea level. The occurrence of recent to subrecent coral rocks above the present sea level bear evidence of recent eustatic changes.

From 15,000 to 8,000 yrs B.P. sea level rose at approximately 1.0-1.25 cms yr^{-1} and there is evidence for a continued, but slower rise of sea level (0.03 to 0.08 $cmsyr^{-1}$) over the last 4,000 years.

In fact, if we consider the present reef level (near the low tide level) at Chiriatapu as reaching its stabilized state (based on community metabolism), then the age of the reef can be calculated to be about 5,000 years, with an initial growth rate of about 6 mm per year. This rate decreased continuously over the period of time to reach its present value of about 0.2 mm per year, with an average growth of about 3 mm per year.

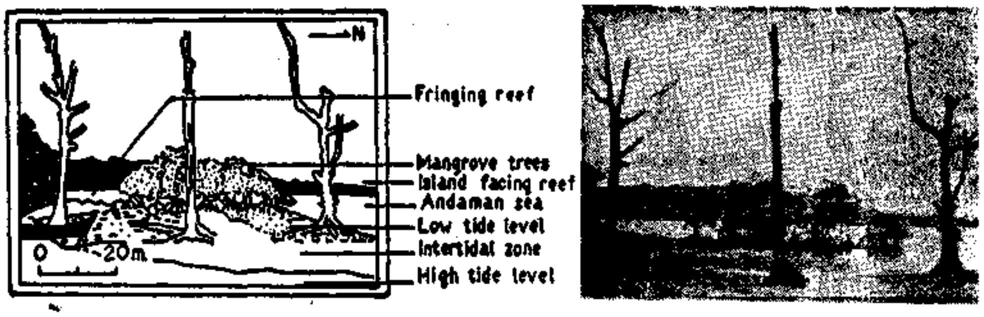

FIG. 7. The location of the leeward fringing reef at Chiriatapu and the surrounding topography.

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