The environmental consequences and management of coral sand dredging in the Suva Region, Fiji.

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THE ENVIRONMENTAL CONSEQUENCES AND MANAGEMENT OF CORAL SAND DREDGING IN THE SUVA REGION, FIJI

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Thesis submitted to the University of Wales
for the Degree of Philosophiae Doctor

July 1983

To my parents
and the peoples of Fiji

DECLARATION

Declaration in accordance with Regulations 11 and 18 for the Degree of Philosophiae Doctor:

I declare that this work is the result of my own investigation and that it has not already been accepted in substance for any degree, nor is it being concurrently submitted for any degree.

All other works referred to in this thesis have been fully acknowledged.

Candidate ..

Supervisor

Date 29/7/83........................

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ABSTRACT

Coral sand is dredged from the seagrass reef flats of fringing and barrier reefs within a 13km radius of Suva. The sand is used in cement manufacture and the present rate of extraction is approximately 100,000 tonnes (dry weight) per annum.

The physical oceanography of the region presents a hydrographic complex of suprareefal marine incursive waters (MIW), demarcated often by sharp fronts from the lagoonal brackish surface waters (LSW). The latter are influenced by the Rewa River discharge and are predominantly a feature of Laucala Bay and Suva Harbour (sites of present and past coral sand dredging). Excavation of pits leads to modification of the back reef hydrography. Current speeds are increased and bottom irradiance reduced, with deleterious effects on habitat restoration. Analogous conditions are not foreseen in the Namuka area (site of proposed dredging) where the LSW is seldom present.

The subtidal back reef seagrass meadows comprise largely monospecific stands of *Syringodium isoetifolium* (Aschers.) Dandy. Sand extraction has caused destruction of the seagrass beds within the dredge pits (ca. 18 hectares to date) but there have been no effects on the immediately surrounding areas. The seagrass beds are exploited by subsistence and part-time commercial fisheries for fish, beche-de-mer and turtles. Net leaf productivity of *S. isoetifolium* (100% cover) is in the order of 0.4g C $m^{-2} day^{-1}$ with a turnover period of ca. 55 days. No evidence was found of seasonal changes in productivity levels.

The rate of sediment accumulation during the Holocene has been in the order of 2.6m $1000y^{-1}$ (radiocarbon dating of cores), equivalent to leeward extension of the reef at a rate of ca. 70m $1000y^{-1}$. The seagrass blades and roots + rhizomes trap, bind and stabilize the sediment and support

a diverse biota which produces sediment *in situ.*

Two approaches to the restoration of biological productivity in the dredged areas were explored. Manual transplantation of *S. isoetifolium* is laborious and technically demanding; the isolated transplants were subjected to heavy grazing by fish and turtles. Artificial reefs were constructed using several different substrates; within 18 months 50 fish species (900 + individuals) were resident in the reef complex and colonies of 3 species of hermatypic corals had become established.

Human activity, spatially far removed from the reef, is adding to the natural environmental stress by increasing suspended sediment loads (and turbidity) through urban/industrial waste discharge and extensive inland soil disturbance, adding to the stress created by dredging the reef sediments themselves.

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1. Introduction

CHAPTER 1. INTRODUCTION.

1.1. Topography.

The Fiji Islands lie between latitude 15°30'S and 20°30'S and straddle the 180° meridian between longitude 177°E and 178°W (Fig. 1.1a). The archipelago comprises about 320 islands of which Viti Levu is the largest, covering 10,000km². The coral reefs of Fiji are not well known. A brief background account is given by Ryland (1982). The maze of reefs around the islands includes all the basic types of reef (fringing, barrier and platform) except for atolls which are not typical of the Fiji Plateau.

The study area, on the southeast coast of Viti Levu (Fig. 1.1b) is located roughly east to west from Nukulau Island to Namuka Island with an outer reef length of 22km. The system of interconnected lagoons separating the barrier reefs from the mainland is divided into three main basins; Laucala Bay, Suva and Namuka Harbours. The reef to the west of Suva, in parts of a fringing type, has a discontinuous lagoon with sections completely enclosed (Plate 1.1a). Several narrow deep passages through the reef give access to the ocean: Nukulau and Nukubuco Passages in Laucala Bay, the main Suva Passage, Rattail and Namuka Passages. At its SW corner, Laucala Bay is connected to Suva Harbour by a narrow channel 10-12m deep. It is also connected to the Rewa Roads by a passage of similar depth between Laucala Point and Nukulau Island.

To the east of the study area lies the delta of the Rewa River, of which two distributaries, the Vunivadra Channel and Vunidawa River, enter the NE corner of Laucala Bay. Average water depth in Laucala Bay is 15-25m, deepening to 40m and more in the Nukubuco Channel. To the west, Nukulau Passage is generally deeper than 40m but is isolated at depth from Laucala Bay by a sill at about 16m. Suva Harbour is 25-35m deep with depths of 80-100m in Suva Passage. Rattail Passage has an entrance sill at 15m with

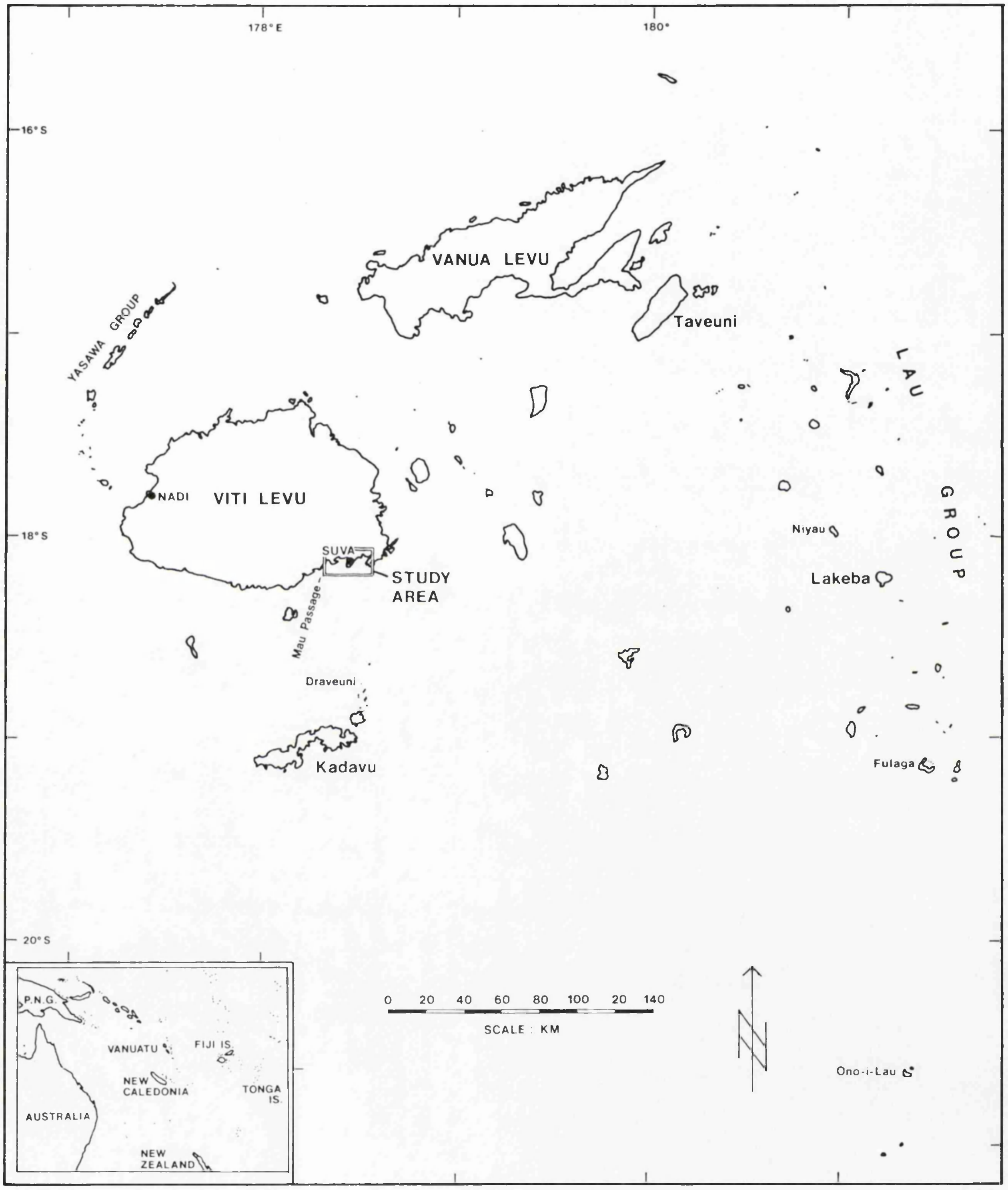


FIGURE 1.1a
The Fiji Islands

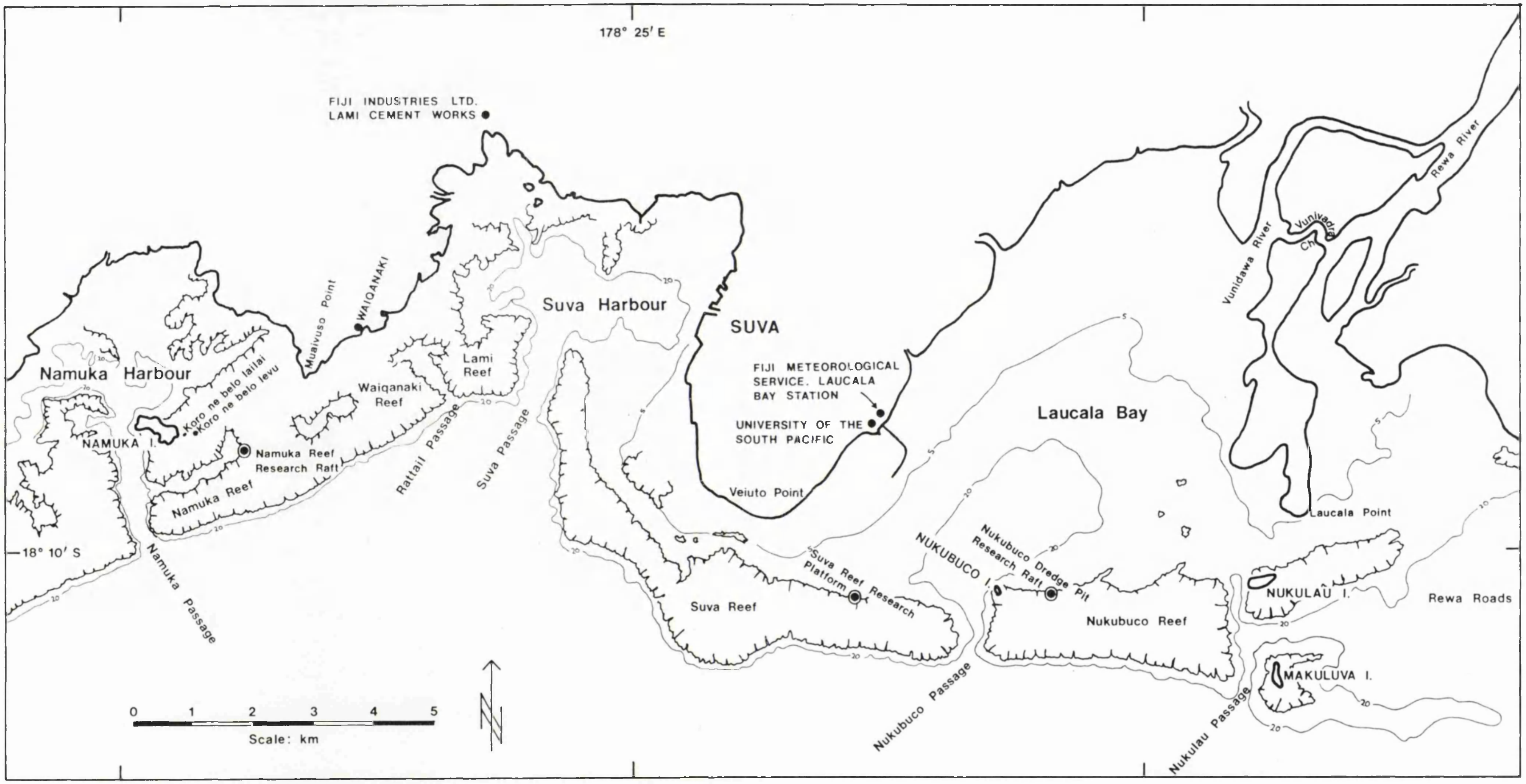


FIGURE 1.1b

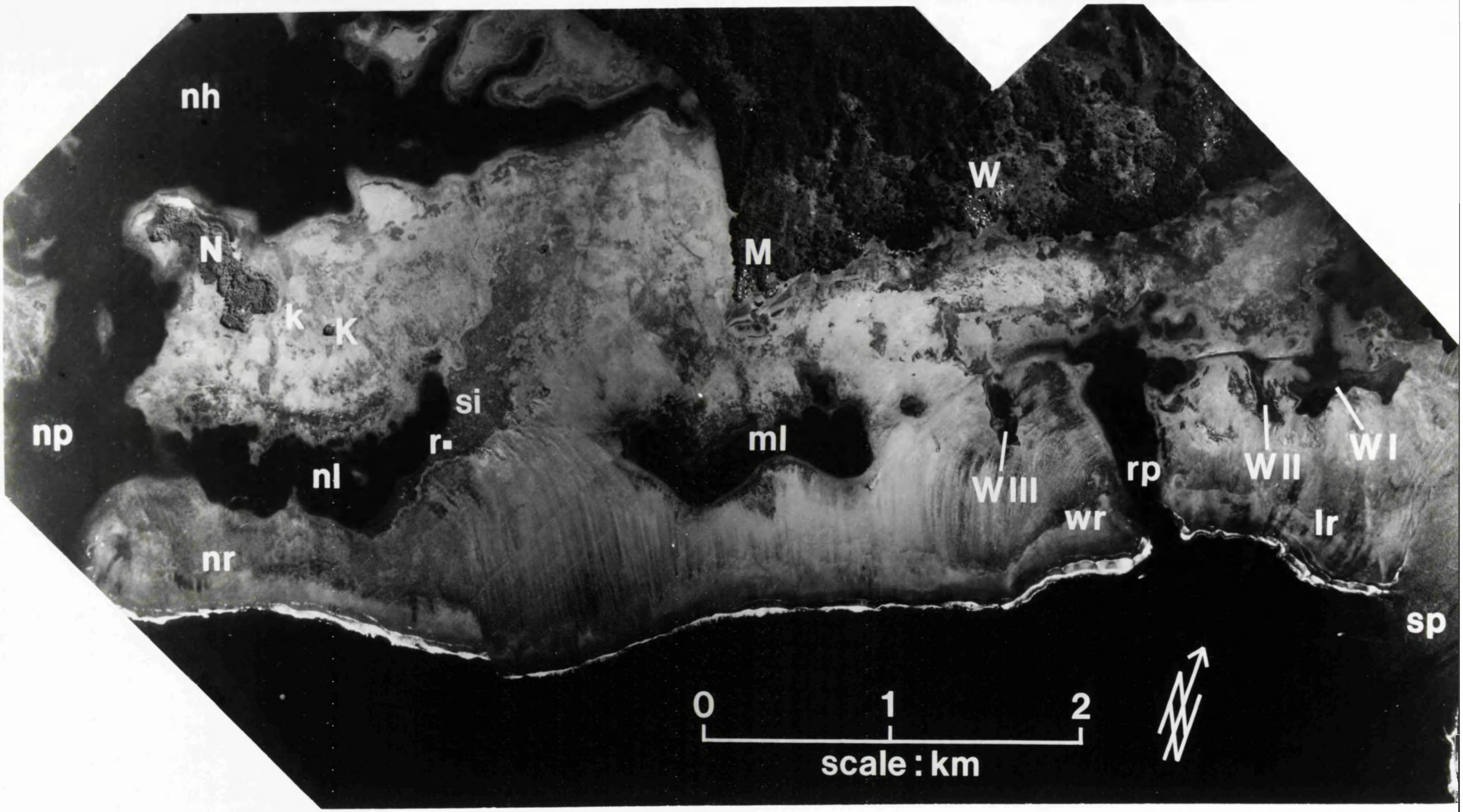
Chart of the Nukulau Island to Namuka Island region (study area). Southeast Viti Levu, Fiji.

PLATE 1.1a

Aerial photograph showing Lami, Waiqanaki and Namuka Reefs

N = Namuka Island
W = Waiqanaki Village
M = Muaivuso Village/Point
K = Koro ne belo levu
k = Koro ne belo lailai
nh = Namuka Harbour
nl = Namuka Lagoon
ml = Muaivuso Lagoon
np = Namuka Passage
rp = Rattail Passage
sp = Suva Passage
nr = Namuka Reef
wr = Waiqanaki Reef
lr = Lami Reef
r = location of research raft on Namuka Reef
si = seagrass meadow, site of proposed sand extraction at Namuka
WI = dredge pit Waiqanaki I
WII = dredge pit Waiqanaki II
WIII = dredge pit Waiqanaki III

See also Fig. 1.1b


nh
N
k
K
si
r
np
nl
nr
M
W
ml
WIII
wr
rp
WII
WI
lr
sp
0
1
2
scale : km

depths of 30m in the small lagoon. Extending eastwards from Namuka Passage (40-50m deep), between the outer barrier reef and Namuka Island, lies an elongate lagoon (Plate 1.1a). This has a maximum depth of 26m but is separated from the passage by an unbroken entrance sill at 9m depth. Of similar dimensions but completely enclosed by the reef is the S-shaped lagoon off Muaivuso Point.

The reefs are variable in width. Nukubuco and Suva Barrier Reefs are generally 1.2-2.0km wide although the NW spur of the latter is less than 1.0km across in places. Lami and Namuka Reefs are of more complex structure. In regions where the reefflat is continuous from the reef crest to the shore (apparently 'fringing' type) widths exceed 2.0km; elsewhere the reef is generally 0.7-0.9km between crest and lagoon. The total intertidal reef area including Nukulau, Makuluva, Nukubuco, Suva, Lami and Namuka Reefs is approximately 28.7km^2.

There are four vegetated islands on the reefs within the study area. To the east, two sand cays, Nukulau and Makuluva Islands, are situated on small barrier-type reefs separated from each other and Nukubuco Reef by deep passages. Makuluvu Island is noted for its instability: since 1951 the island has been relocated on the reef such that only 10% of the present island is common to the 'original'. Nukubuco Islet (Plate 1.1b) is a low-lying sandbank on the NW corner of Nukubuco Reef. Having been used as a target for bombing practice during WWII, Wright (1969) reported that during the early 1960s the islet was immersed to a depth of 30cm at high water. Between 1979 and 1982 the central core of the island was stable, above HWS and with a well vegetated area of approximately 560m^2 (31 May, 1979). At the western edge of the study area lies Namuka Island, a 'high' island, approximately 16m high with two small islets, Koro-ne-belo and Koro-ne-belo-lailai immediately to the east and roughly in line with Muaivuso Point.

PLATE 1.1b

Aerial photograph showing sections of Nukubuco and Suva Reefs

N = Nukubuco Island

lb = Laucala Bay

sr = Suva Reef

nr = Nukubuco Reef

np = Nukubuco Passage

rp = location of research platform on Suva Reef

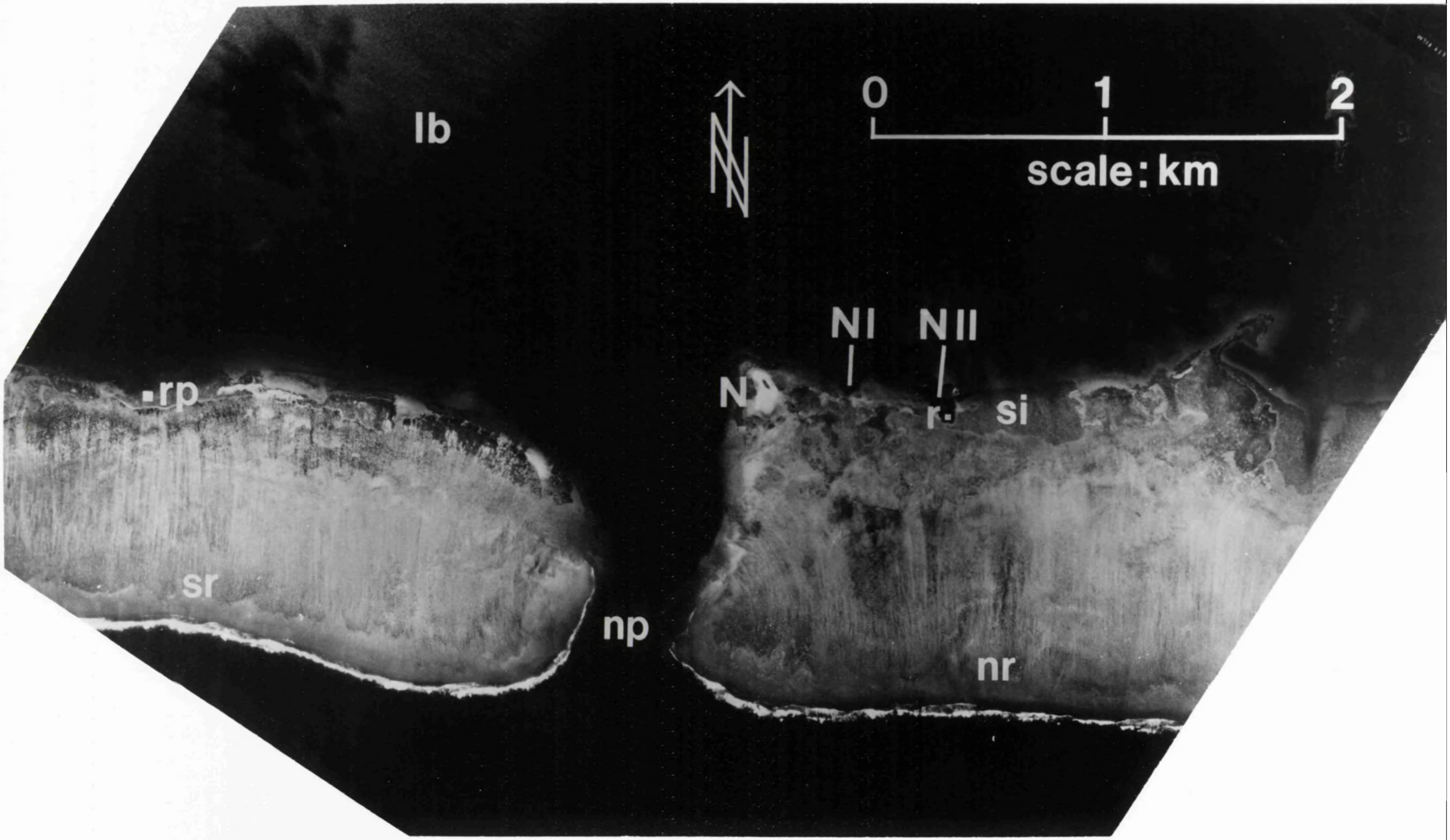
r = location of research raft on Nukubuco Reef

si = seagrass meadow

NI = dredge pit Nukubuco I

NII = dredge pit Nukubuco II

See also Fig. 1.1b


lb
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sr
np
nr

1.2. Climate.

Climatic data were obtained from the Fiji Meteorological Service (FMS) station situated on the northwestern shore of Laucala Bay, adjacent to the University (Fig. 1.1b). Continuous records of wind speed and direction, air temperature, rainfall, sunshine and atmospheric pressure were all available for the duration of the study. Similar records dating back to 1943 were available at the FMS Headquarters in Nadi and the long-term averages have been derived either from these records or from FMS Information Sheets (FMS I.S.).

1.2.1. Winds.

At all seasons the predominant winds over Fiji are the trade winds from the east or SE. These are most persistent between June and November (FMS I.S. No. 35, 1979). From November to April the Fiji Group is influenced by the northerly monsoon system, characterised by a general drop in wind strength and the occasional occurrence of cyclones.

Figure 1.2.1a shows a ten year analysis (1961-1970) of wind data from Laucala Bay. Of all the winds with a speed greater than 1.5m s^{-1}, 70% of observations were from the E or SE octants. There is considerable interannual variability in wind patterns. Figure 1.2.1b shows the weekly mean wind speed for the period May 1979 to October 1980. Between June and September 1980 the trade winds were consistently more strongly developed than during the corresponding period in 1979. The peaks seen during the periods 23-30 March 1980, 4-11 May 1980 and 17-24 August 1980 are all attributable to the climatic phenomenon known by Fijians as *bogiwalu* (literally translated, "8 days of wind"). These winds, generally from the E or SE octants, occasionally from the S or SW, are often responsible for building up heavy surf on the reef, completely preventing reef emergence even on low spring tides.

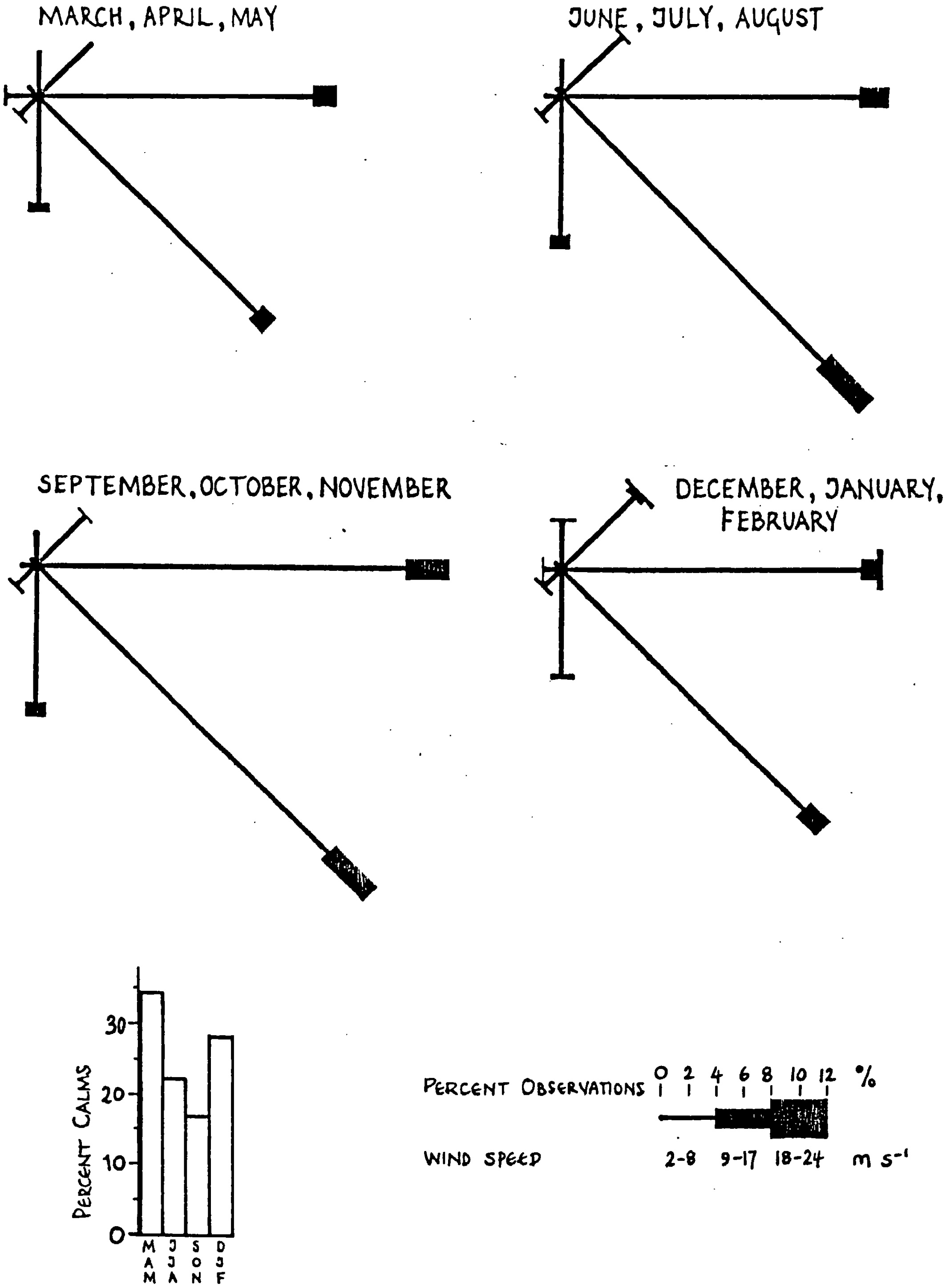


FIGURE 1.2.1a

Seasonal variation in surface wind speed and direction at Laucala Bay.
Based on observations at 0000, 0600, 1200 and 1800 FST in the period 1961-1970 inclusive. Wind roses indicate relative frequencies, percent, from eight direction octants, subdivided according to speed. 0 to 1.5m s^{-1} is taken as calm. Source: FMS I.S. No. 42, 1979.

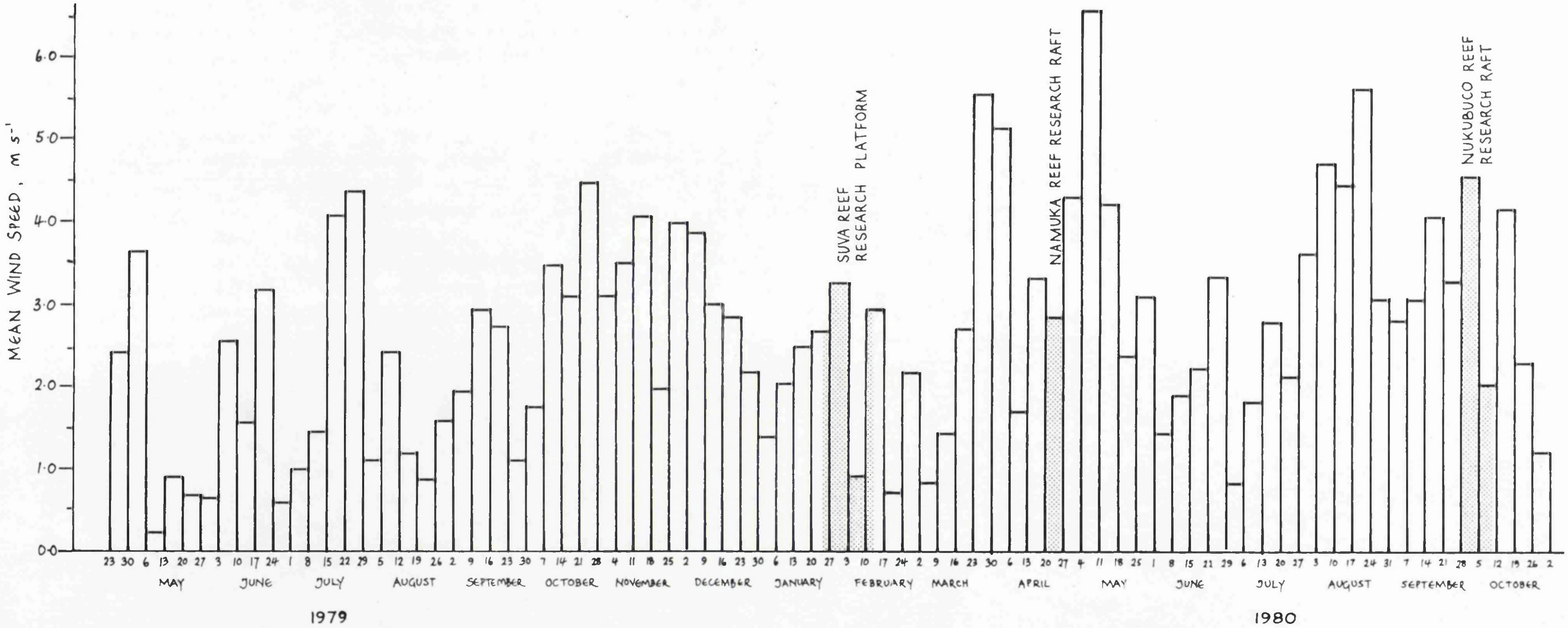


FIGURE 1.2.1b

Weekly mean wind speed at Laucala Bay in the period May 1979 to October 1980. Periods of intensive oceanographic observation are indicated.

Detailed analyses of wind speed and direction (hourly observations) for discrete periods of intensive study are presented with the oceanographic observations (Chapter 2).

1.2.2. Cyclones.

Cyclones in Fiji are mostly confined to the period November to April, with greatest frequencies around January and February. On average some ten to twelve severe cyclones per decade affect some part or other of Fiji (FMS I.S. No. 35). Movement of the cyclones is irregular but is generally between SE and SW, towards higher latitudes (FMS I.S. No. 31). For a period during the cyclone, winds are frequently from the N and NE octants, particularly significant since they may impinge on backreef areas normally well protected from the prevailing SE winds. Under certain conditions, the combination of reduction in atmospheric pressure (lowest barometric pressure recorded at Laucala Bay: 958.4mb, 28.1.52) and violent winds circulating around the centre of the cyclone will cause storm surges. During Cyclone *Meli* (27 March 1979) a storm surge of 2-3m was recorded at the island of Niyau, 240km E of Suva (FMS I.S. No. 46). Further hazards associated with cyclones include high seas, and prolonged, torrential rain, followed by flooding of the nearshore reefs and lagoons.

The effects of two severe cyclones were experienced in the study area during the 1978/79 and 1979/80 seasons. Cyclone *Meli* (26-28 March 1979) reached hurricane force in Central Lau and Kadavu (see Fig. 1.1a) and storm force in southeastern Viti Levu (study area), with a toll of 52 dead. Cyclone *Wally* (3-5 April 1980) reached only gale force but the torrential rain in southeastern Viti Levu (Section 1.2.4) caused severe flooding, land erosion and the loss of 16 lives. The ensuing exceptional discharge of brackish, sediment-laden, waters caused significant mortalities of organisms on both fringing and barrier reefs (Ryland et al., 1983).

1.2.3. Air Temperature.

Figure 1.2.3. shows the annual pattern of monthly mean maximum and minimum daily temperatures for Laucala Bay (1942-1980). Average temperatures change only 3-4°C between the coldest part of the year (July-August) and the warmest (February).

1.2.4. Rainfall.

The geographic pattern of rainfall throughout the Fiji Group is highly variable on account of the mountainous nature of the main islands. On Viti Levu the heaviest rainfalls occur on the windward, SE, side of the island. At Laucala Bay the mean annual rainfall is 3050mm (cf. Nadi, on the 'dry' side, 1900mm), with a wet season : dry season ratio of 3:1. Figure 1.2.4a shows the month by month variation in mean daily rainfall (mm) taken from May 1979 to October 1980. Although much of the rain falls as brief local showers, an occasional slow-moving weather system brings fairly general rain to a larger area. These events show up clearly, notable occasions being the storm of 4/5 May 1979 and the exceptional rains associated with Cyclone *Wally*, 3-5 April 1980. In the latter case, rainfall during an unrestricted 24 hour period exceeded 900mm at two recording stations in SE coastal ranges and the storm produced two day rainfall totals exceeding 500mm over an approximate 1800km^2 area of SE Viti Levu (Harris, 1980. PWD., Hydrology Section, Flood Report, 12/5/80). These episodic events have far-reaching effects on the study area due to the outflow there of the Rewa and several minor rivers which drain a large part of SE Viti Levu (Section 1.2.5).

1.2.5. River Runoff.

The SE, high-rainfall area of Viti Levu (Fig. 1.2.5a), with a catchment area of 2920km^2 (Mr. Lloyd Harris, PWD Hydrology Section, pers. comm.), drains through a system of four rivers which merge as the Rewa River. The annual

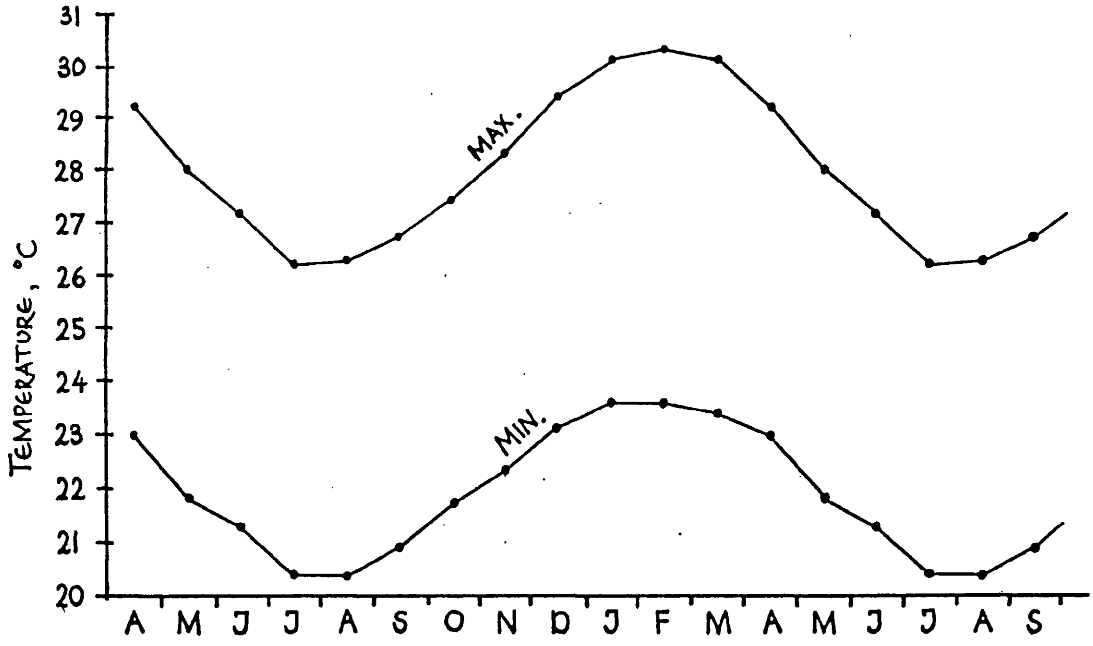


FIGURE 1.2.3

Annual pattern of monthly mean maximum and minimum daily temperatures at Laucala Bay.
Based on observations in the period 1942-1980.

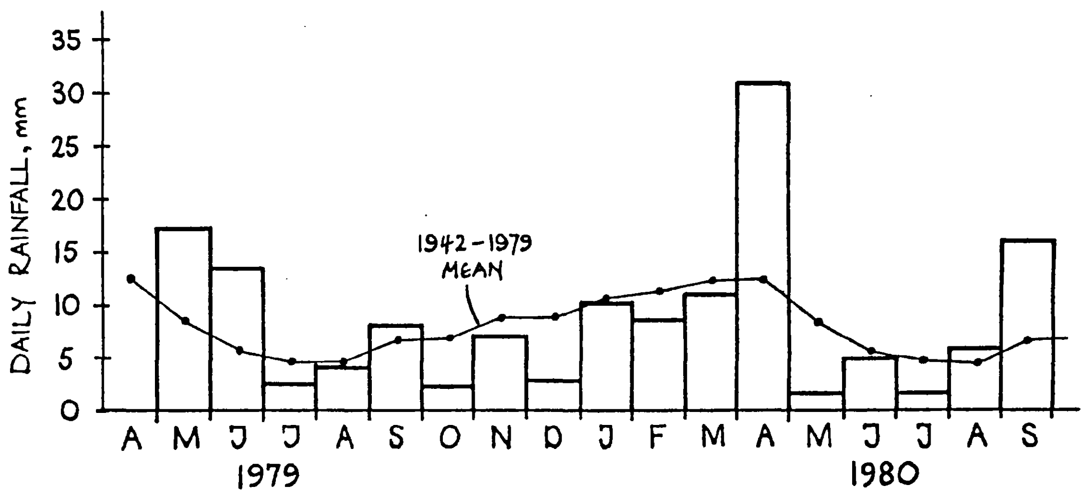


FIGURE 1.2.4a

Month by month variation in mean daily rainfall at Laucala Bay in the period May 1979 to September 1980.
Long term means, based on observations in the period 1942-1979 are indicated.

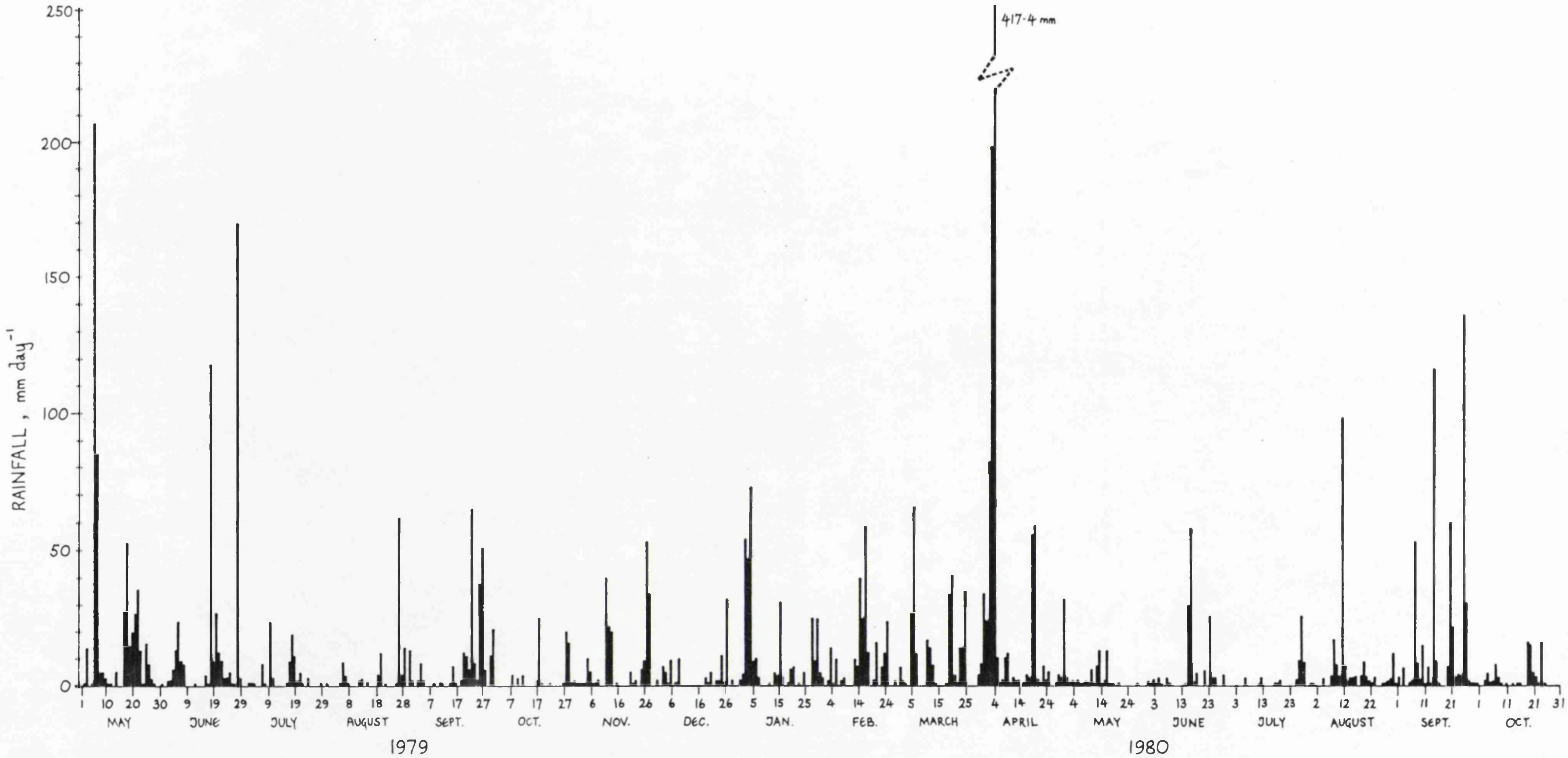


FIGURE 1.2.4b

Daily rainfall at Laucala Bay in the period May 1979 to October 1980.

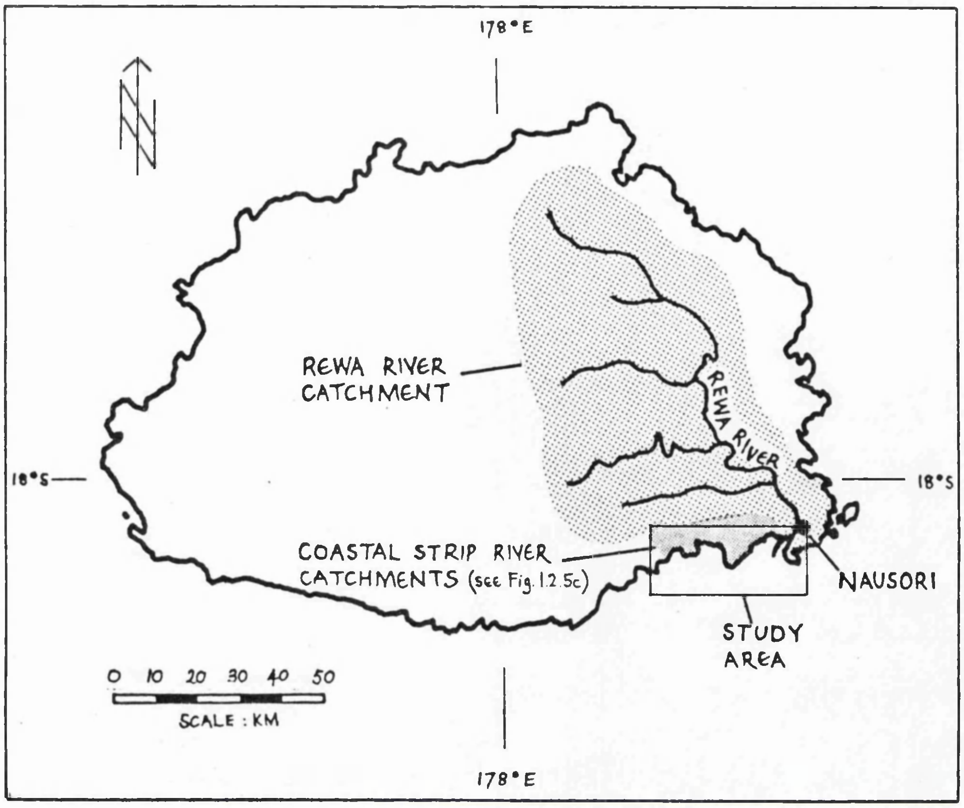


FIGURE 1.2.5a

River catchments affecting the Nukulau Island to Namuka Island region, SE Viti Levu.

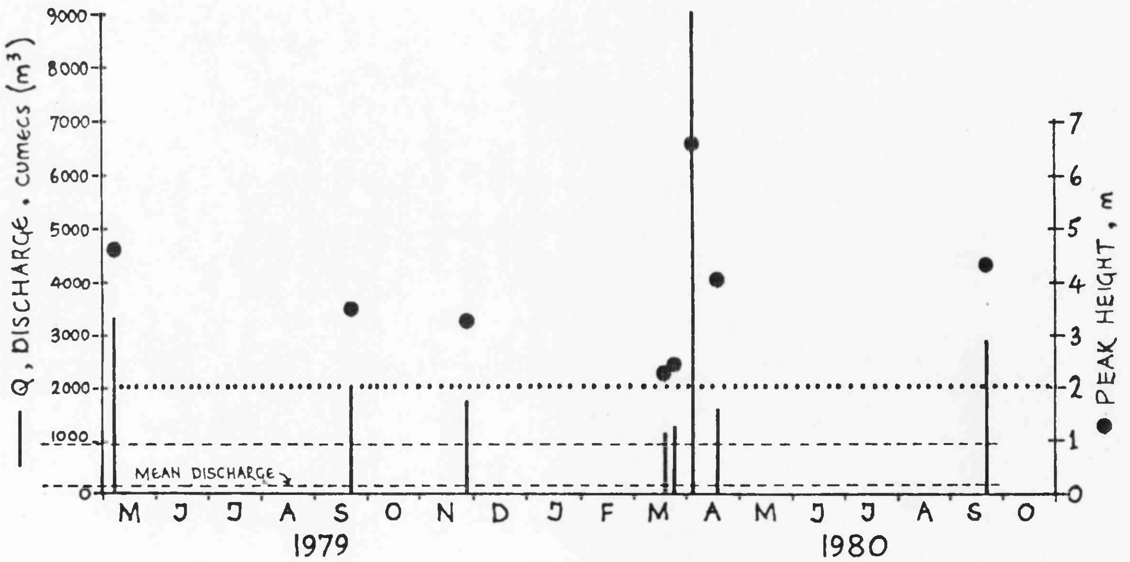


FIGURE 1.2.5b

Peak flood levels over 2m (gauged height) and corresponding discharge values (Q) gauged at Nausori Pump Station in the period May 1979 to October 1980.
Based on information supplied by the Hydrology Section, Public Works Department, Fiji Government.

mean discharge of the Rewa, at Nausori, estimated by gauging of all the tributaries, is 156m^3 s^{-1} (Mr. Lloyd Harris, pers. comm.). Rewa river level is gauged at Nausori Pump Station, but up to a height of 2m the record is complicated by tidal effects; above this level, equivalent to a discharge of 960m^3 s^{-1}, a rating curve has been constructed. Figure 1.2.5b shows peak flood levels over 2m, with corresponding discharge values, at Nausori Pump Station for the period May 1979 to October 1980. The floods of 5-6 May 1979 and 3-4 April 1980 are evident, the latter producing a peak discharge of 9000m^3 s^{-1}, nearly 60 times the mean value. Due to the local variability in rainfall over the sizeable catchment area, not all floods in the Rewa are associated with high rainfalls at Laucala Bay, and vice versa.

Gaugings by Caldwell Connell Engineers (In: Commonwealth Department of Transport and Construction et al., 1982) show that about 15% of the Rewa discharge is distributed by the Vunivadra Channel and Vunidawa River into the head of Laucala Bay, the remaining 85% via the Rewa and Nasoata Rivers (Fig. 1.2.5c). Several smaller rivers exit along the SE coast of Viti Levu and directly affect the Nukulau to Namuka area (Fig. 1.2.5c). In Laucala Bay the Nasinu, Samabula and Vatuwaqa rivers discharge along the NW shore. The Tamavua, Lami, Wailekutu and Veisari rivers empty into the head of Suva Harbour and Namuka Harbour is supplied by several creeks, the Naikorokoro and Wainaiburu being the most important. These rivers and creeks drain a narrow catchment area seldom exceeding 5km inland. Neither average nor peak discharge values are available for these rivers. However, mean discharge values have been estimated using catchment areas derived from Figure 1.2.5c and assuming an annual mean runoff per unit area equal to that of the Rewa catchment: $5.3 \times 10^{-2} m^3 s^{-1} km^{-2}$. The results of these calculations are shown in Table 1.2.5. Annual mean discharge of the combined

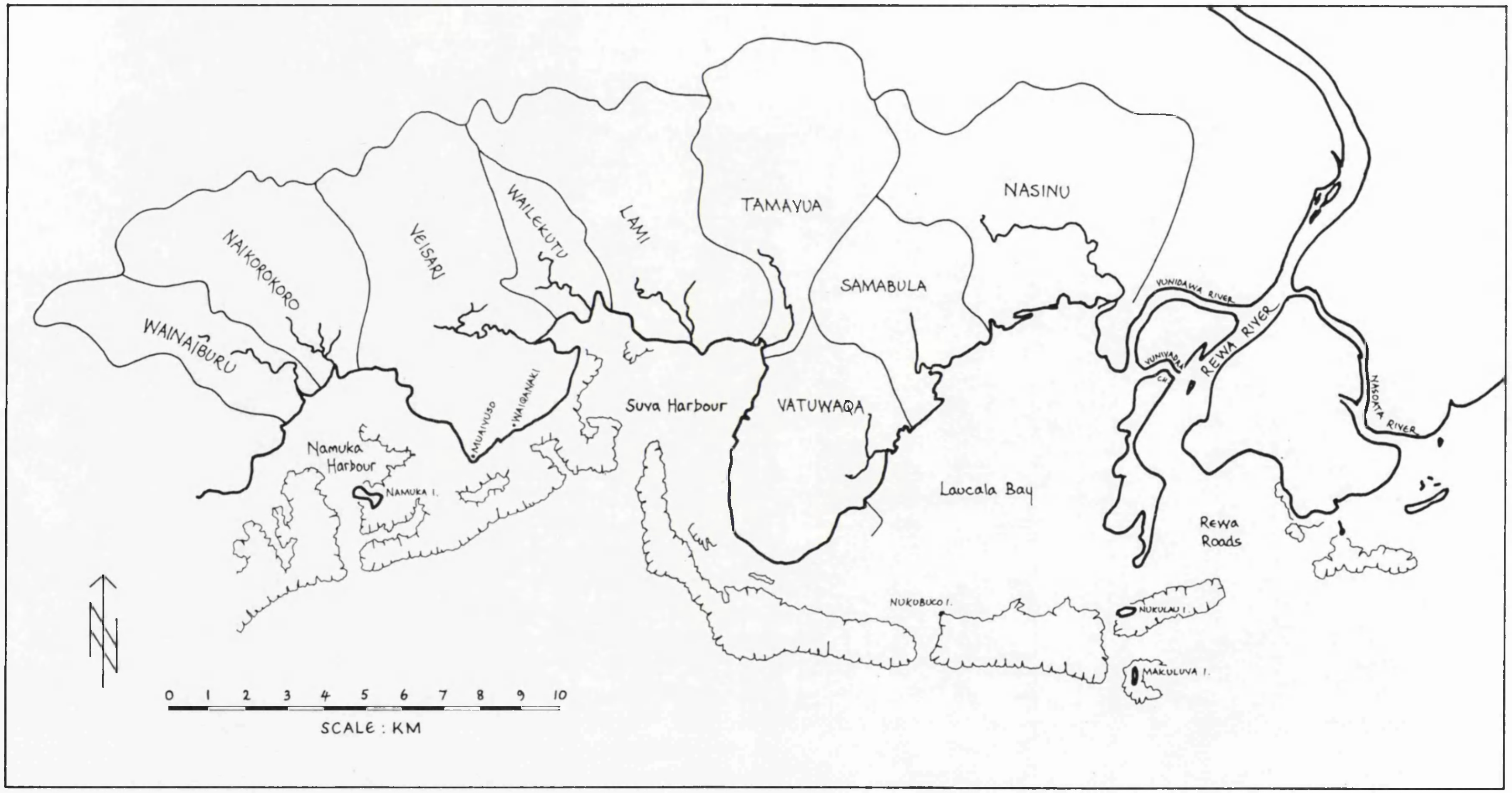


FIGURE 1.2.5c
Coastal strip river catchments affecting the Nukulau Island to Namuka Island region.

TABLE 1.2.5. ESTIMATED ANNUAL MEAN DISCHARGE (m^3 s^{-1}) OF THE MAJOR RIVERS INFLUENCING THE AREA FROM NUKULAU ISLAND TO NAMUKA ISLAND, S.E. VITI LEVU.

River	Catchment Area, km^2	Estimated Mean Discharge, m^3 s^{-1}
Rewa	2920	156.0
Vunivadra/Vunidawa	Distributary of Rewa	23.4
Nasinu	33.4	1.8
Samabula	13.6	0.7
Vatuwaqa	15.9	0.8
Tamavua	24.5	1.3
Lami	24.7	1.3
Wailekutu	6.5	0.3
Veisari	29.7	1.6
Naikorokoro	19.6	1.0
Wainaiburu	11.7	0.6

Sources: Rewa (Mr. Lloyd Harris, Fiji Public Works Dept., Hydrology Section).
Vunivadra/Vunidawa (Commonwealth Department of Transport and Construction et al., 1982).
Nasinu-Wainaiburu (by calculation from (i) mean annual runoff per unit area for Rewa catchment - see above; (ii) estimated catchment areas - see Figure 1.2.5b).

minor rivers in the Nukulau to Namuka area is estimated to be 9.4m^3 s^{-1}. This is equivalent to 6% of the annual mean discharge of the Rewa or 40% of the estimated proportion of that flow entering the head of Laucala Bay via the Vunidawa River and Vunivadra Channel.

Of the water discharged via the main Rewa river mouth, a portion is swept through the channel between Laucala Point and Nukulau Island into Laucala Bay, the amount depending on the wind and tide conditions.

1.2.6. Sunshine.

Figure 1.2.6a shows the daily duration of bright sunshine averaged over each week during the study period. Variation in monthly mean daily duration of bright sunshine, taken from 37 years of data (1943-1979) is shown in Figure 1.2.6b. Daily sunshine values reach a maximum during December and gradually decline to a minimum during July and September. Comparative data for the period May 1979 - October 1980 are also shown. Two periods of prolonged, above average, sunshine were recorded: December 1979 to February 1980 and May to July 1980. April and September 1980 were particularly cloudy months recording only 73% and 59% of the long term average sunshine values respectively.

1.3. Oceanography.

1.3.1. Tides.

The tides in Fiji are predominantly semi-diurnal with a mean range of 1.1m. There is disagreement with the literature concerning tidal levels. The values given in the Fiji Marine Department Nautical Almanac (1979) differ considerably from those in the Admiralty Tide Tables, Vol. 3, 1980 (Table 1.3.1) and neither set of values adequately describes the 1979-1980 tidal predictions. In the former, the H.A.T. is given as 1.89m (*cf*. 2.2m in the Admiralty Tables) above chart datum, yet in the same volume there are several predicted tides of 1.9m and 2.0m. The significance of sea level

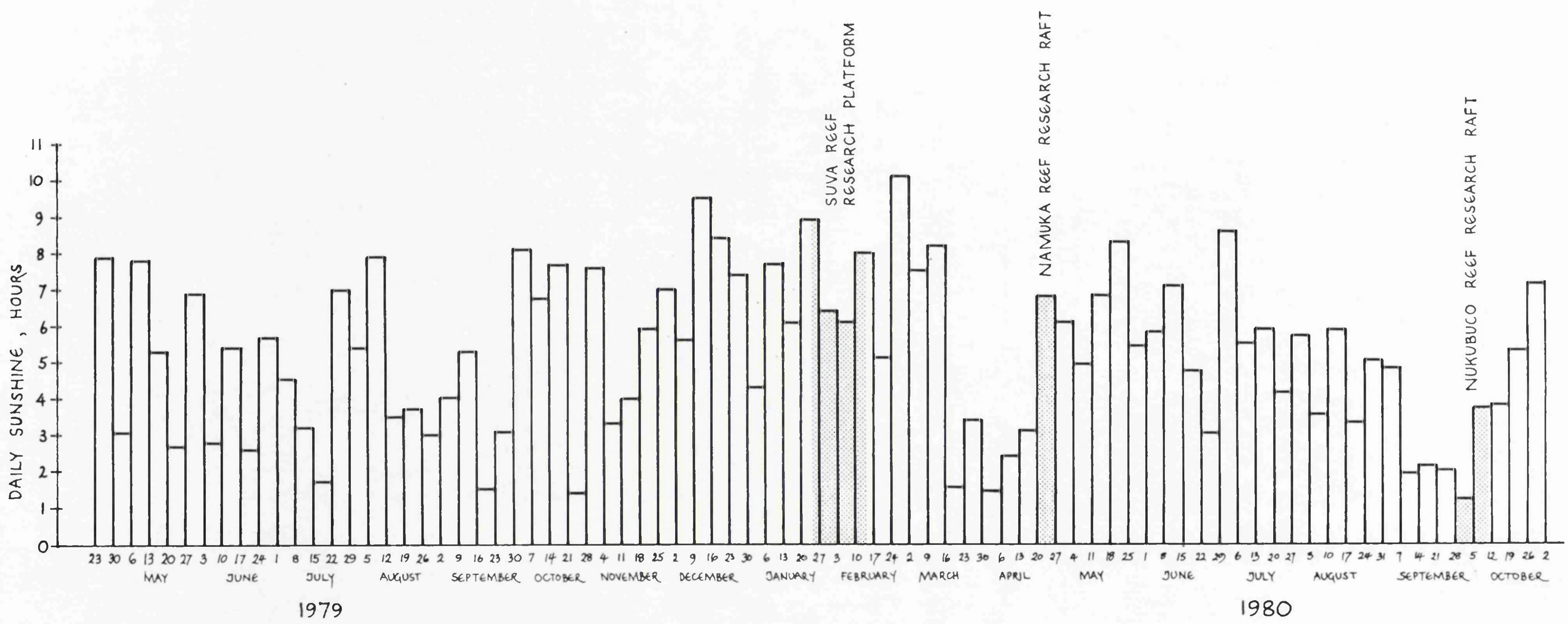


FIGURE 1.2.6a

Daily duration of bright sunshine at Laucala Bay, averaged over each week in the period May 1979 to October 1980.

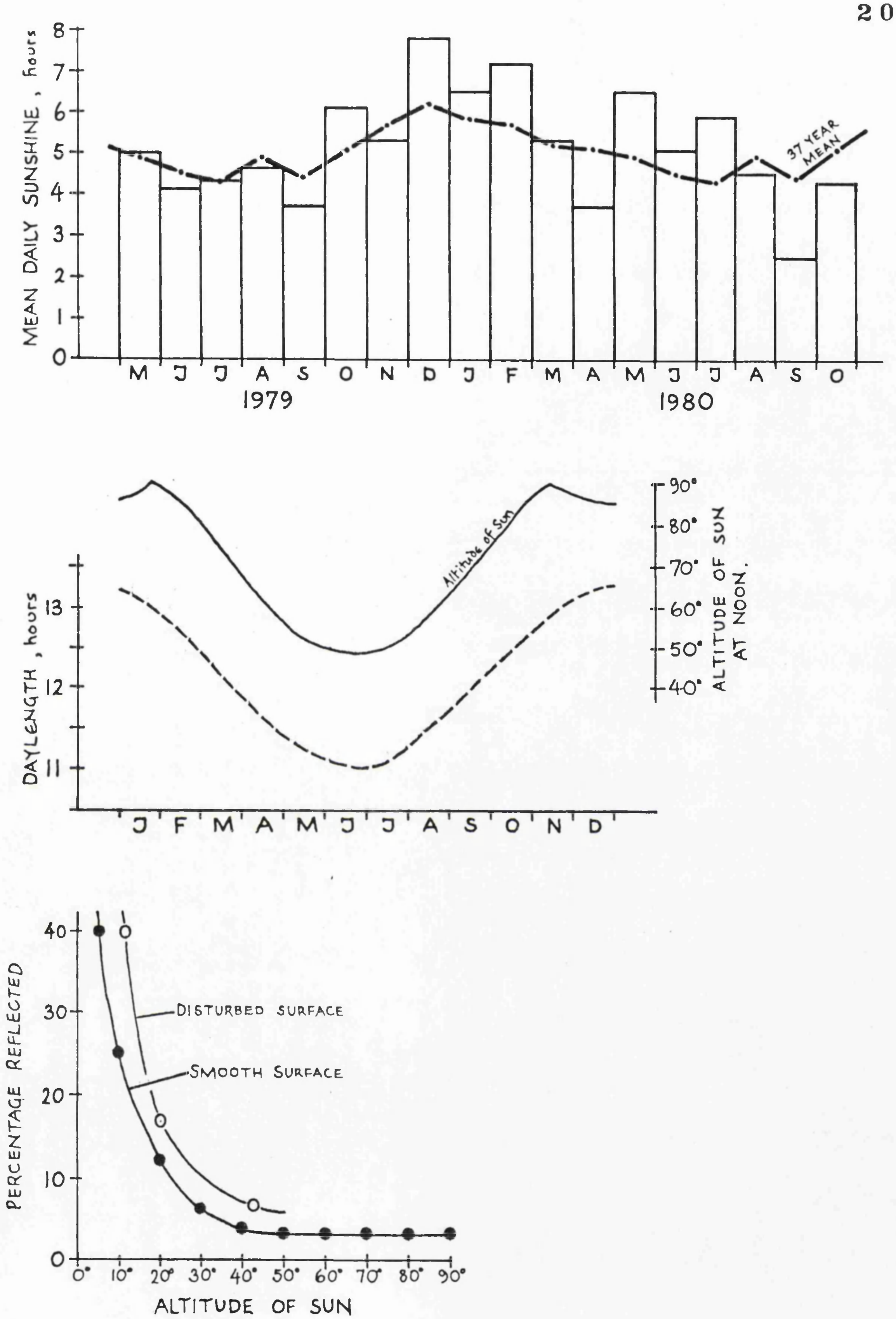


FIGURE 1.2.6b

i) Month by month variation in mean daily bright sunshine at Laucala Bay in the period May 1979 to October 1980. Long term means, based on observations in the period 1943 to 1979 are indicated.

ii) Annual variation in daylength and altitude of sun at noon, at Laucala Bay.

iii) Reflection of solar radiation at the sea surface. (See Dietrich et al., 1980; Sverdrup et al., 1942).

TABLE 1.3.1. TIDAL LEVELS (METRES ABOVE CHART DATUM) FOR SUVA, FIJI.

	Fiji Marine Dept. Nautical Almanac 1979	Admiralty[1] Tide Tables Vol. 3, 1980	By Calculation[2] From Admiralty Predictions, May 1979 - April 1980
HAT	+ 1.89	+2.2	
MHWS	+ 1.64	+1.9	
MHWN	+ 1.43	+1.7	
MSL	+ 0.98	+1.1	
MLWN	+ 0.49	+0.8	+ 0.64
MLWS	+ 0.27	+0.6	+ 0.38
LAT	+ 0.03	0.0	
CHART DATUM	0.0	0.0	

Notes:

1. Admiralty Tide Tables Vol. 3; tidal levels predicted from one year of observations (1976) by the Fiji Harbour Authority.
2. Height of MLWS taken as the average, over 12 months, of the heights of two successive low waters during those periods (approx. once a fortnight) when the range of tide is greatest (Admiralty Tide Tables, Vol. 3., 1980). Similarly for MLWN when the range of tide is least.

measurements in reef ecological surveys is emphasized by Pugh and Rayner (1981) and in this study the level and timing of low water and their annual variability are of particular importance. Figure 1.3.1a shows the predicted heights of low water between May 1979 and April 1980. Using the definitions of tidal levels as given in the Admiralty Tide Tables Vol. 3 (1980), MLWN and MLWS were calculated (Table 1.3.1). The timing of extreme low water will affect the degree of exposure of the emersed and shallow-water reef areas to solar radiation (Farrow and Brander, 1971). Ryland (in press) points out that in Fiji, the lowest ebb falls by night in the hottest months and by day in the coolest months. Figure 1.3.1a illustrates this point and also shows that whereas during the cooler months daytime ebbs are generally C.D. +0.5m or below, during the hottest months daytime ebbs seldom fall below C.D. +0.5m.

Commonwealth Department of Transport and Construction et al. (1982) state that mean sea level at Suva varies from month to month and year to year in the range 0.8m to 1.3m (no source given). Sea level may be affected by several factors. The possible occurrence of storm surges associated with the dramatic drop in atmospheric pressure associated with cyclones has already been noted (Section 1.2.2.). Longer term variation in atmospheric pressure also affects the sea level. Figure 1.3.1b shows the annual variation in monthly mean barometric pressure at Laucala Bay. Pressure is at a minimum (1007.5) in February (the cyclone season) and a maximum (1014.0) in July and August (the tradewind season). A reduction in pressure of 1mb is equivalent to a rise in sea level of 10mm. Thus annual variation in barometric pressure at Laucala Bay may be accountable for an increase in MSL during the summer months in the order of 65mm. Short-term variation may be seismically induced. The 1953 Suva earthquake caused slumping of marine sediments and the resulting tsunami caused extensive damage to the

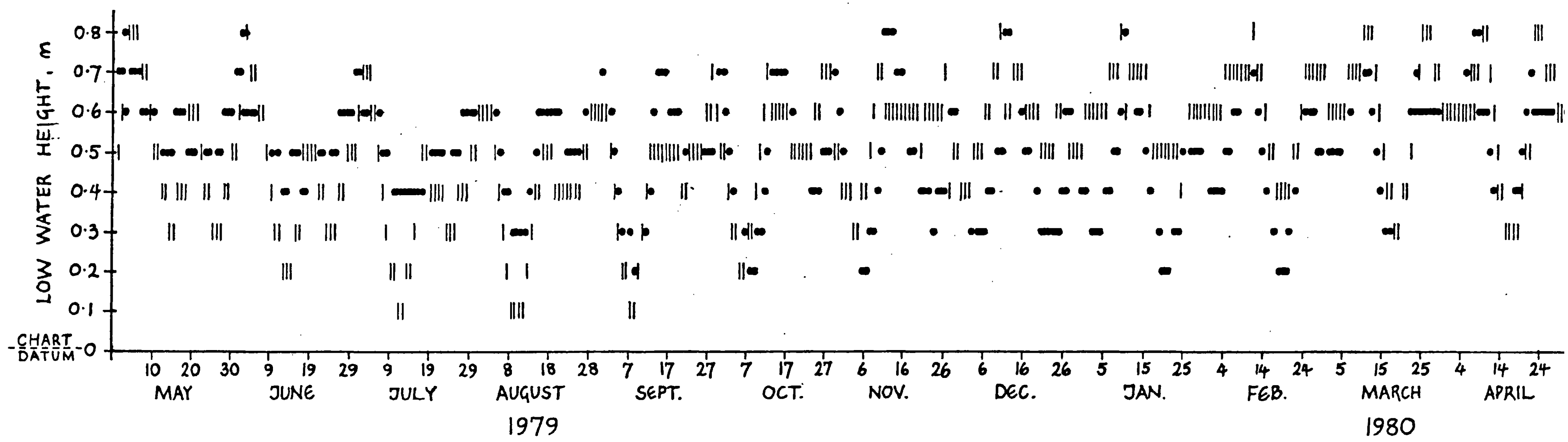


FIGURE 1.3.1a

Predicted heights of successive low waters at Suva in the period May 1979 to April 1980 (Admiralty Tide Tables Vol. III, 1979, 1980).

| = daytime low water (0600-1800 hrs); ● = nighttime low water (1800-0600 hrs)

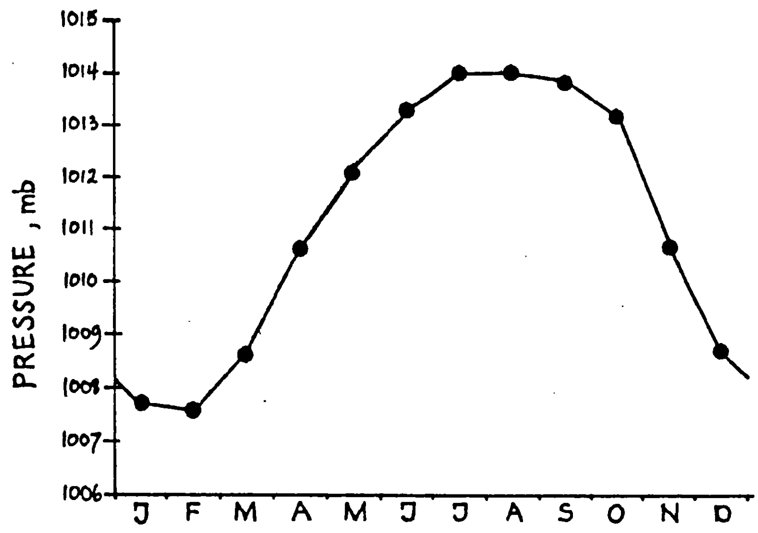


FIGURE 1.3.1b

Annual pattern of montly mean barometric pressure at Laucala Bay. Based on hourly observations in the period 1942-1965.

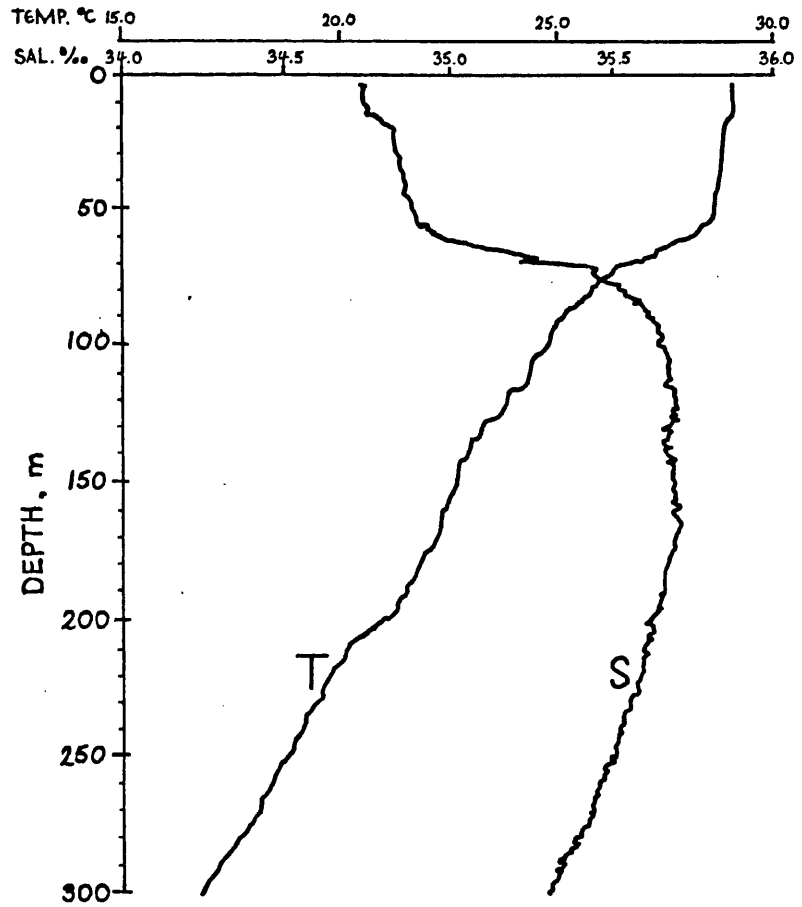


FIGURE 1.3.2.1a

Temperature and salinity profiles for a station south of Mau Passage, SE Viti Levu (see Fig. 1.1a). March 3, 1979. 0700h. From Webster, 1979.

reef and shoreline (Houtz, 1963). The islands of Nukulau and Makuluva were swept by a wave 2m high.

1.3.2. Seawater Temperature and Salinity.

1.3.2.1. Outside the reef.

Water depths of 2000m are achieved within 20km S of the reefs bordering SE Viti Levu (British Admiralty Chart 2691). The water column in these depths comprises a surface water mass largely isolated from deeper waters by a pycnocline lying from 50-70m deep (Fig. 1.3.2.1a). The surface waters are a mixture of South Equatorial Water and Central South Pacific Water (Rochford, 1959) with a salinity range of 34.75 to 35.00°/oo (Donguy and Henin, 1976). Figure 1.3.2.1b shows sea surface temperatures derived from charts of ten year means (Edwards, 1979) and, for the duration of this study, from weekly charts (NOAA, 1979-1983). Temperatures reach a maximum of 28.0-29.5°C during February/March and a minimum of 24.5-25.5°C during August/September. There is considerable interannual variation: particularly noticeable is the peak early in 1980. Offshore, the homogeneity of this surface layer is generally maintained by wind/wave induced vertical mixing (Webster, 1979), but there is an upper, relatively weak pycnocline at 15-20m (Fig. 1.3.2.1a), marking the lower boundary of the more brackish (34.7°/oo) surface water above the more saline (34.8-35.00°/oo) water of the main upper water mass. Below 50m the main pycnocline is marked by an increase in salinity and decrease in temperature. Between 100m and 180m a salinity maximum of 35.5-36.0°/oo marks the core of the Subtropical Lower Water. Below this, between 650m and 1100m, lies the Antarctic Intermediate Water, characterized by a salinity minimum, typically 34.4-34.5°/oo. The bottom waters are derived from the Antarctic Deep Water (Brandon, 1973; Pickard *et al.*, 1977; Wyrtki, 1962).

1.3.2.2. In the lagoons.

Little work has been done on the oceanography of the backreef and

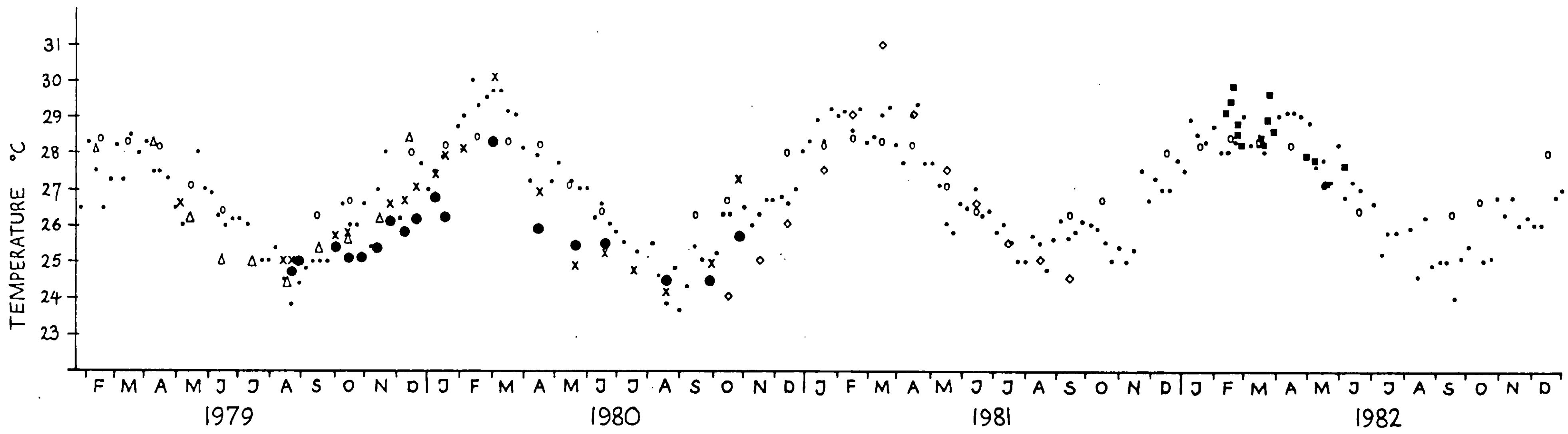


FIGURE 1.3.2.1b

Seawater temperature data for Laucala Bay and area immediately offshore of SE Viti Levu.

- • = surface; offshore, 18°S, 180° meridian; weekly obsns.; NOAA (1979-1983)
- o = surface; offshore; monthly mean (10 year average); Edwards (1979)
- Δ = surface; Laucala Bay; monthly mean; Fiji Government, Fisheries Division (pers. comm.)
- ◇ = surface: Laucala Bay; discrete observations; Comm. Dept. Trans. Constr. et al. (1982).
- x = surface; Laucala Bay Stn. 3; discrete observations; this study, Section 2.1
- ● = 40m below surface; Laucala Bay Stn. 3; discrete observations; this study, Section 2.1
- ▪ = surface; Laucala Bay; discrete observations; this study, 2nd fieldwork period

lagoon areas between Nukulau I. and Namuka I. One notable exception is the recent study of the inner, NE, area of Laucala Bay pending the extension there of sewage effluent discharge from Kinoya (Commonwealth Dept. of Transport and Construction et al., 1982). A strong salinity stratification was noted in the bay during most of the year although substantial variations in salinity profiles were found from one fortnight to the next. The surface water, with a typical salinity of 25-30°/oo, overlies water of 34°/oo or more. The upper, fresher, layer was found to average 6m deep in the wet season and 1-1.5m in the dry season. Surface water temperature for the period October 1980 to September 1981 ranged from 24°C to 31°C, from a minimum in October to a maximim in March (Fig. 1.3.2.1b).

There are reports on the physical oceanography of several other lagoons in the SW Pacific, particularly that of the Great Barrier Reef. Brandon (1973) states that the vertical salinity profile on the Queensland shelf is isohaline for the majority of the year. Vertical gradients may form during the summer (wet) season as a result of diminished wind force and influx of freshwater. The freshwater tends to remain on the surface and undergo further warming. Thus the surface layer becomes even less dense and the stratification more stable. However, a relatively short period of strong winds can readily mix the entire water column and destroy the gradient. Using a plot of density (σ_t) versus time, Pickard et al. (1977) showed that, at the surface, both temperature and salinity play a role in the stability of the water column. At depth (28m), where conditions are almost isohaline throughout the year, density variations are mainly due to temperature changes (data from Orr (1933a) from Low Isles, northern GBR). A similar situation, with a well-mixed water column except during the wet season is also reported in the New Caledonia barrier reef lagoon (Rotschi and Magnier, in Pickard et al., 1977).

1.3.3. Currents.

1.3.3.1. Outside the reef.

At all times of year the Trade Drift flows through the Fiji Group in a W to SW direction. Off SE Viti Levu current speed ranged from 0.19m s^{-1} to 0.32m s^{-1} with a maximum in March-April (Wyrtki, 1960). Immediately offshore of the reef to the W of the study area, Webster (1979) measured currents during early March 1979. Water movement was generally tide dependent in a longshore direction, eastwards on the flood, westwards on the ebb, with maximum velocities of 0.1m s^{-1}.

1.3.3.2. Inside the lagoon.

Commonwealth Dept. of Transport and Construction et al. (1982) conducted drogue, current meter and dye experiments in Laucala Bay. These showed that the brackish upper water layer tends to be wind driven although it moves with the tide during prolonged periods of calm. Flow of the deeper layer shows a tidal rhythm; northerly on the flood, southerly on the ebb. During April 1981, net deep water movement was 300m tidal cycle^{-1} northwards, in August-September 1981, 620m tidal cycle^{-1} southwards. No measurements were made near the backreef or in the reef passages.

1.3.3.3. Over the reeftop.

The importance of wave-driven currents on a windward barrier reef (Bikini Atoll) was first quantified by von Arx (1948), who measured reeftop currents with an average speed of 0.5m s^{-1} into the lagoon. Munk and Sargent (1954) observed on the reefflat, mean water levels 0.5m higher than the surrounding ocean. These higher water levels, due solely to waves breaking on the reef, created the suprareefal currents measured by von Arx. Tait (1972) used the term "wave set-up" to describe the wave-built super-elevation of water. He showed that full "set-up" could only be achieved on a model reef where the lagoon had no connection to the open sea. Since this is rarely, if ever, so, "set-up" is only at its peak value (the highest elevation of water above the surrounding ocean) at the seaward edge of the reef flat. When wave conditions are sufficient that "set-up" is achieved, currents will tend to flow in across the reef and back out to the ocean through either the subsurface or channel connections. Von Arx calculated that on Bikini Atoll, of the tidal prism, one third came over the reef, the remainder through the passages. Lagoonwards reeftop currents of 0.5-1.0m s^{-1} (high tide) were observed on Addu Atoll (West Coast of India Pilot, quoted by Stoddart, 1966). On Enewetok Atoll, Maragos (1978) measured currents of between 0.1m s^{-1} (low tide) and 1.2m s^{-1} (high tide) across the reef.

1.3.4. Waves.

Few wave data are available for the Fiji Group. Figure 1.3.4a shows sea and swell data derived from U.S. Naval Oceanographic Office charts (1943). Both sea and swell are predominantly from the E or SE throughout the year. Direction is more variable during the summer months when there are significant swells from the S and SW and seas from the NE. The sea data, as is to be expected, shows a positive correlation with the wind data for Laucala Bay (Fig. 1.2.1a).

The reef protects Laucala Bay from the ocean swell. Wind waves of short period and wavelength are generated within the bay. A typical trade wind of 8m s^{-1} will generate waves of 0.4-0.6m height, 2-3 seconds period; stronger winds (17m s^{-1}) will generate waves 0.8-1.3m high (Commonwealth Dept. of Transport and Construction *et al.*, 1982).

1.4. History of Sand Extraction in the Suva Region.

1.4.1. Cement Manufacture in Fiji.

Cement is manufactured in Fiji by Fiji Industries Ltd., whose factory is situated at Lami, 5km W of Suva (Fig. 1.1b). Production of cement began

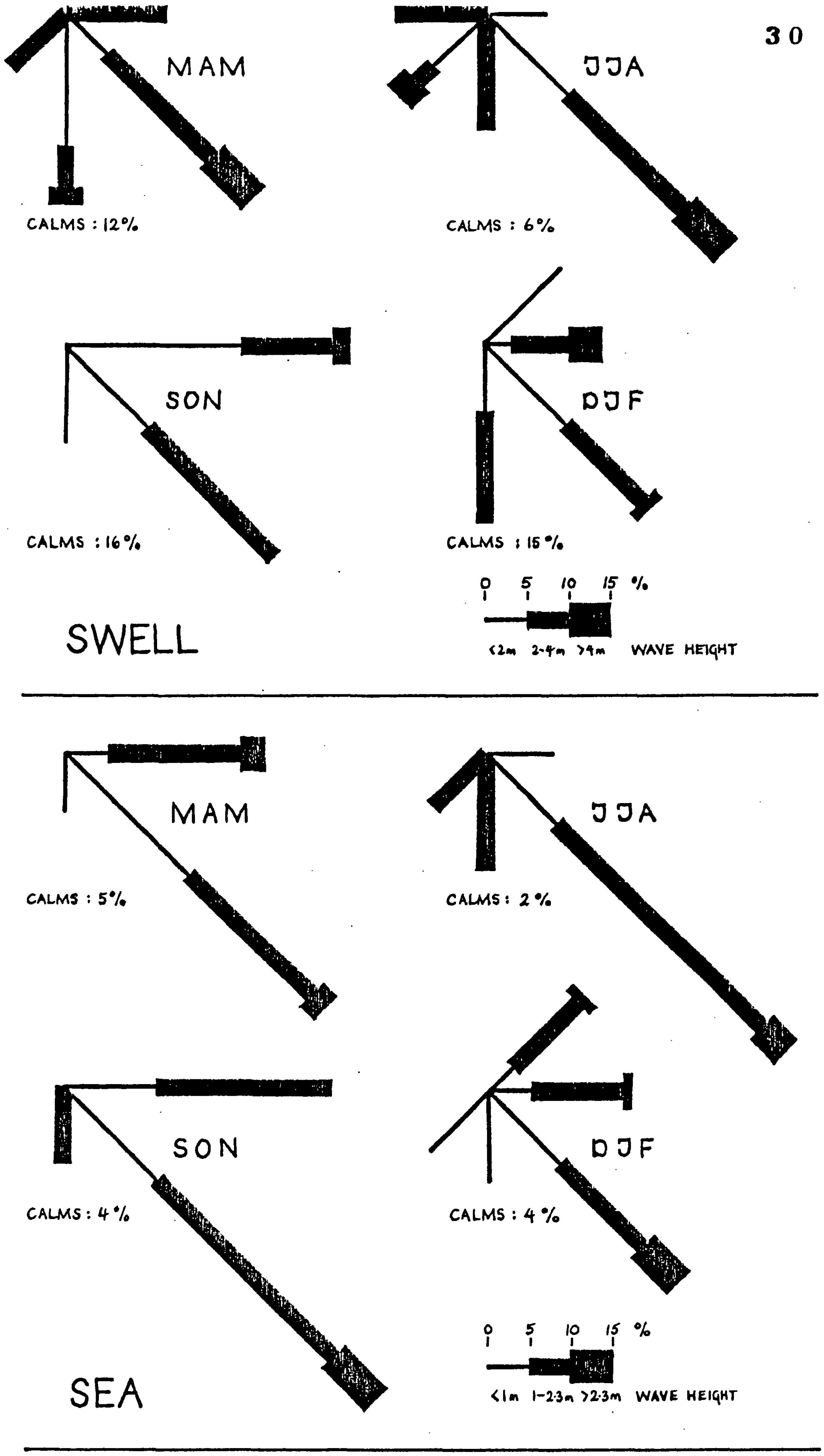


FIGURE 1.3.4a

Sea and swell data for the area immediately offshore of SE Viti Levu. Based on U.S. Naval Oceanographic Office Charts (1943).

in 1962 and by 1979 total annual production was 87,414 tonnes. The company employs about 200 people and, in addition to supplying all the demand for cement within Fiji, exports to many other South Pacific nations (including Western Samoa, Tonga, Kiribati, Tuvalu and Vanuatu).

The basic raw materials are carbonate and silica sands. The carbonate sand is extracted from the lagoon side of accessible reefs using a grab dredge. For the silica sand a suction dredge is used, normally deployed at the mouth of the Vunidawa River (Fig. 1.1b). The sands are transported by barge to the cement works at Lami.

Although the carbonate sand is generally termed 'coral sand', it comprises skeletal debris from several phyla of calcareous organisms including red and green algae, corals, molluscs, echinoderms and foraminfera.

Mineralogically the sand consists of aragonite and calcite with a small fraction of magnesian calcite. The magnesium carbonate content of the sand presently dredged by Fiji Industries Ltd. is quite tolerable, ranging from 2.6-3.4% (Krishna, 1979). For the manufacture of Portland cement a maximum of 4% may be tolerated: an important feature of the coral sand is that the $MgCO_3$ is distributed very evenly, unlike some reef rocks which have bands of high concentration of $MgCO_3$ as dolomite or dolomitised limestone. The loose nature of the backreef sediments also contributes to the ease of the dredging operation: no cutting or blasting is required. Furthermore, because of the absence of large blocks in the sand, it can be milled directly without costly pre-crushing.

1.4.2. Carbonate Sand Extraction 1962-1983.

The carbonate sand is extracted from the backreef areas where the depth of loose, easily won, material exceeds 10m in thickness. The surface of the deposits generally lies 0-2m (-4m) below C.D. and suitable extraction sites are reliably indicated by the presence of submarine seagrass meadows and adjacent areas of bare sand. The meadows are found in a zone 50-200m (exceptionally, -600m) wide along the backreef of Nukubuco and Suva Reefs and to a lesser extent on Lami and Namuka Reefs. The extent of the seagrass meadows, prior to sand dredging, is shown in Figure 1.4.2a. The sand is excavated to a depth of 7-10m (below C.D.), the depth limit being imposed by the machinery being used. Due to the restricted capacity of the winding drum, the cranes have potential to lift from greater depths only if a smaller diameter cable is used. In turn this means a reduction in grab size and ultimately the operation is no longer cost effective.

During the first 10 years of operation, sand was dredged from Lami Reef, the sand reserves closest to the cement works (Fig. 1.4.2b, area: Waiqanaki I). During 1972, as these deposits became depleted, a channel was blasted to connect Suva Harbour to Rattail Passage. This provided the sand barges sheltered access to sand deposits off Waiqanaki village (areas: Waiqanaki II and III). With nearing exhaustion of these deposits towards the end of 1975, dredging operations were moved to Suva Reef, off Veiuto Point (area: Suva), where the extensive seagrass beds indicated suitable sand reserves. Due to local opposition to dredging in this area the mining lease was withdrawn early in 1976 and for 9 months the dredgers returned to the sites Waiqanaki I and III. In 1977 the sand dredgers returned to Laucala Bay to the more distant Nukubuco Reef (areas: Nukubuco I and II) where they have remained until 1983 (Plate 1.1b).

The manufacture of 1 tonne of cement requires 1.2 tonnes carbonate sand (K. van Vlyman, pers. comm.). Between 1962 and December 1979 approximately 1.23×10^6 tonnes of sand were dredged (Table 1.4.2a) reaching a sustained level of approximately 1.0×10^5 tonnes y^{-1}.

An areal analysis of the reefs within the bounds of the study area, the Rewa Roads to the E and Namuka Passage to the W, was made from aerial photographs of 1951, 1967, 1978 and 1979 (Appendix I). Measurements were

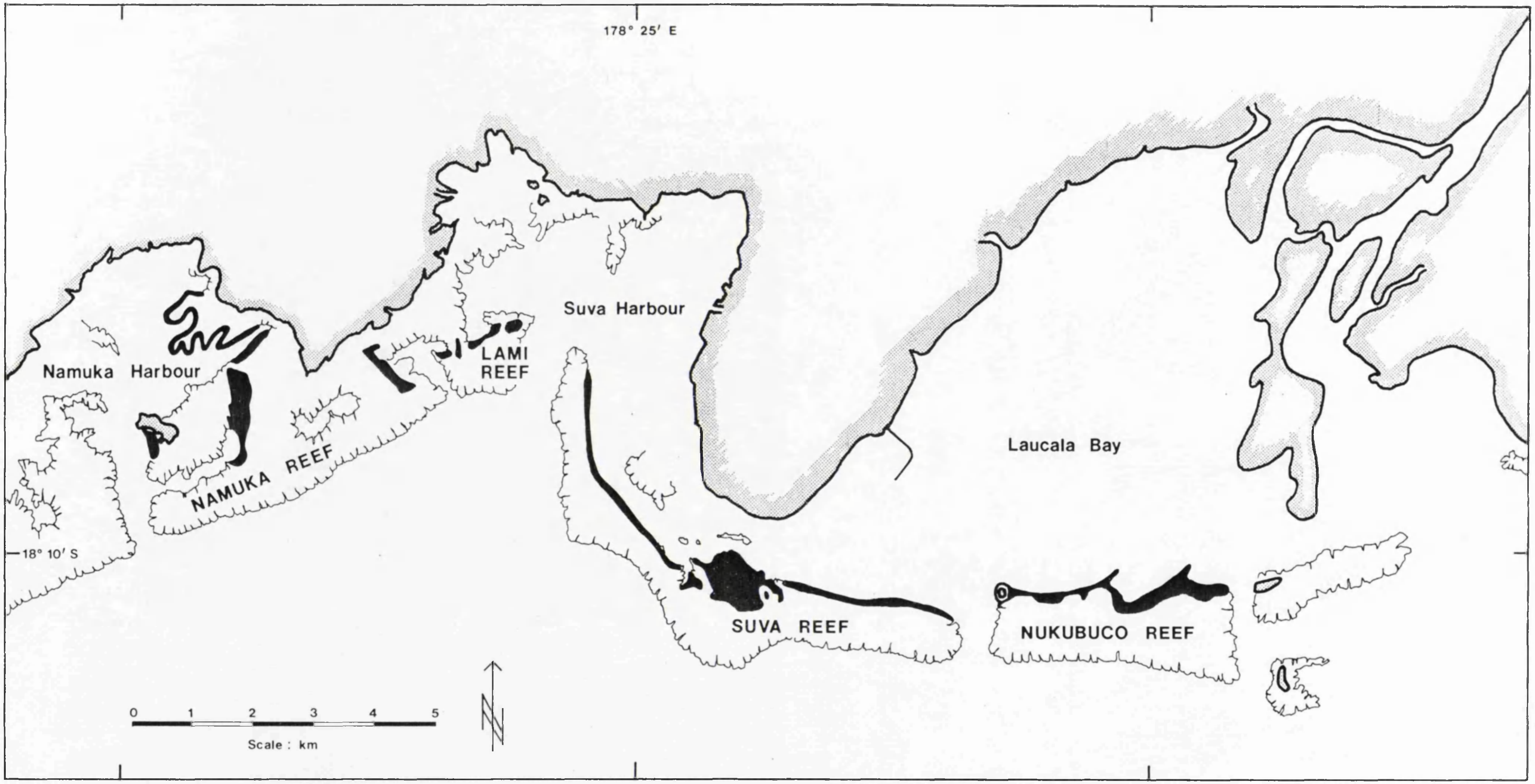


FIGURE 1.4.2.a

Distribution of back reef seagrass meadows (prior to any sand extraction) in the Nukulau Island to Namuka Island region.

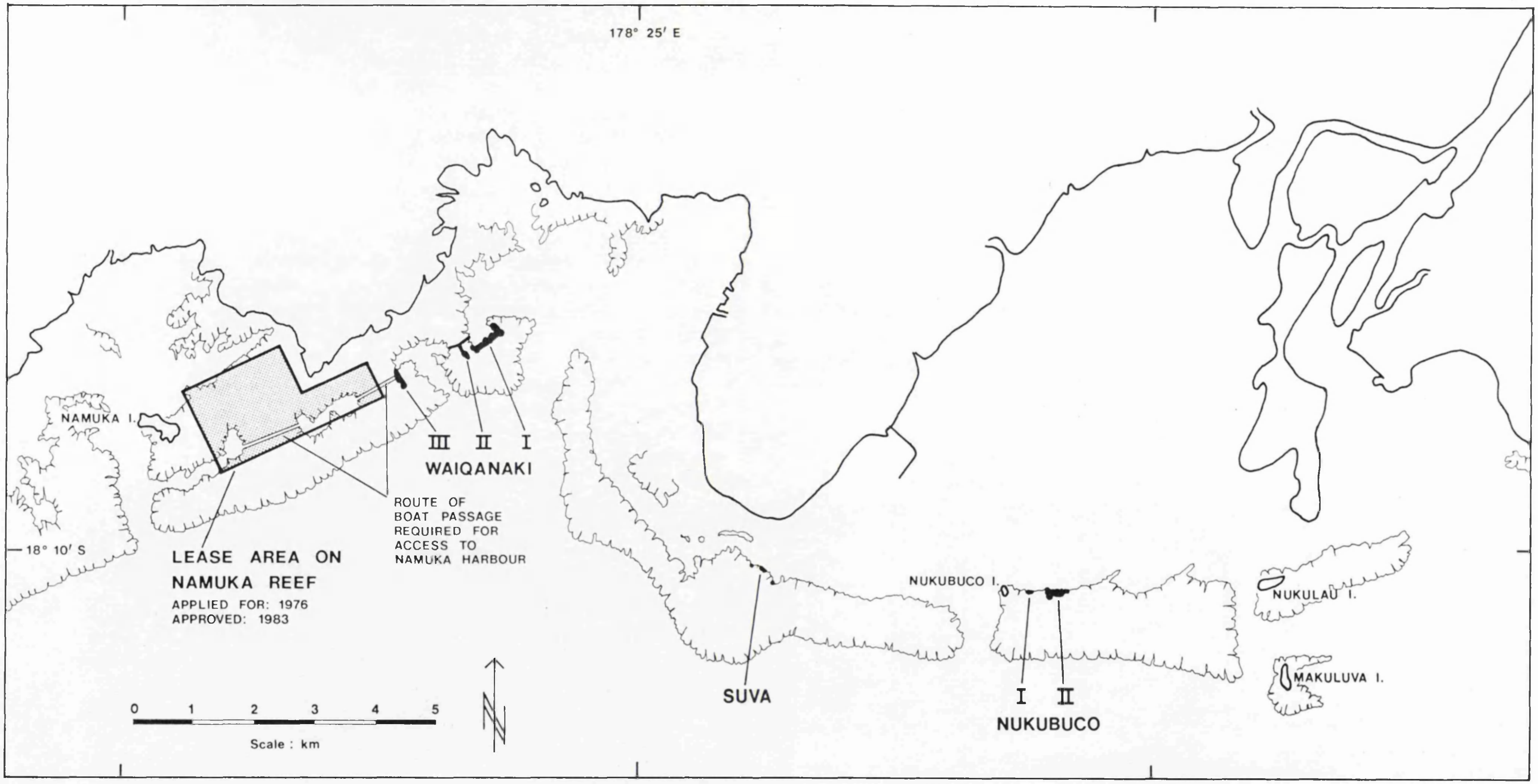


FIGURE 1.4.2b

Locations of past, present and proposed sites of sand dredging.

TABLE 1.4.2a. CORAL SAND EXTRACTED BY FIJI INDUSTRIES LTD., 1962-1979. AMOUNTS IN TONNES. SEE ALSO FIGURE 1.4.2b; LOCATIONS OF DREDGE PITS.

	Waiqanaki			Suva Point	Nukubuco	Total
	Area I	Area II	Area III			
1962-Sept 72	553416					
Sept 72-end 73		80000				
End 73-01/01/75			14000			773416
01/01/75-20/10/75			64873			
20/10/75-01/01/76				14235		79108
01/01/76-07/03/76				9060		
07/03/76-01/01/77	18848*		50000			77908
01/01/77-15/02/77			10183			
15/02/77-01/01/78					83406	93589
1978					99925	99925
1979					107184	107184
TOTAL:	572264	80000	265056	23295	290515	1231130

*Old areas second time mined.

made of the area of the reefs, the seagrass meadows prior to excavation and the dredge pits (Table 1.4.2b). Excavation of sand between 1962 and 1979 directly impacted 12.48 of a total reef area of 2610 hectares. The dredged areas included an estimated 6.30 ha of established seagrass representing 3.4% of the total meadows in the Nukulau to Namuka region. The remainder of the excavations (6.18 ha) impacted open sandy bottom communities (Section 3.6.). By comparison of the aerial photographs of 18/6/78 and 31/5/79, the impacted area over 11.5 months was 1.24 ha, i.e., 1.29 ha y^{-1}. Assuming a sustained level of impact, it is estimated that a further 5.16 ha of backreef area was impacted between 1979 and 1983. Thus, it is estimated that up to May 1983 the extraction of coral sand will have directly impacted 17.64 of a total 2610 ha of reef (0.67%). Of the 17.64 ha of dredge pits, 50-55% were originally covered by well established seagrass, representing a destruction of 8.82-9.70 ha; 4.7-5.2% of the total meadows.

Since the depth of dredging is limited by water depth, the shallower the sea bed prior to excavation, the greater the available sediment reserve. Between 1962 and May 1979, 1.15×10^6 tonnes of sand (K. van Vlyman, pers. comm.) were extracted from an area of 12.48 ha (this analysis). The in situ density of the sand is 1.22 tonnes m^{-3} (K. van Vlyman, pers. comm.). The mean thickness of the extracted sediment reserve was therefore:

$$\frac{1.15 \times 10^6}{1.22 \times 12.48 \times 10^4} \qquad \text{N.B. 1 hectare} = 1 \times 10^4 m^2$$

$$= 7.55m$$

This is consistent with observed dredge pit depths of 7-10m and seabed depths prior to dredging of 0-2m (-4m) below C.D.

1.4.3. Proposed Site of Future Sand Dredging.

By 1980 the cement works at Lami had a maximum production capacity of 1.0×10^5 tonnes y^{-1}, requiring 1.2×10^5 tonnes y^{-1} carbonate sand.

TABLE 1.4.2b. AREAS OF (i) REEFS (ABOVE CHART DATUM); (ii) SEAGRASS MEADOWS PRIOR TO DREDGING; (iii) DREDGE PITS; (iv) SEAGRASS MEADOWS DESTROYED BY EXCAVATION TO MAY 1979.

Reef	Dredge Pit	Reef Area	Seagrass Area Prior To Dredging	Seagrass Area As A % Of Reef Area	Excavated Areas to May 1979			
					Excavated Area	Exc. Area As % of Reef Area	Seagrass Area Destroyed By Excavation	Exc. Seagrass As % Seagrass Prior To Dredging
		hectares	hectares	%	hectares	%	hectares	%
Lami and Namuka	Waiqanaki I	1160	4.7	3.0	4.92	0.42	2.35	67.0
	Waiqanaki II				1.36	0.12	0.80	
	Waiqanaki III		3.1		2.36	0.20	1.53	49.4
	Namuka*		26.8		NO EXCAVATION TO DATE (1983)			
Suva	Suva	880	91.6	10.4	0.68	0.08	0.34	0.4
Nukubuco	Nukubuco I	570	61.0	10.7	1.00	0.18	0.20	0.3
	Nukubuco II				2.16	0.38	1.08	1.8
Total		2610	187.2	7.2	12.48	0.48	6.30	3.4

Areas measured from aerial surveys of August 1951 (1:16,000), June-July 1967 (1:24,000), June 1978 (1:20,000) and May 1979 (1:20,000). All areas refer to the reefs in the study area, bounded by the Rewa Roads to the east and Namuka Passage to the west.

*Namuka: proposed site of future excavation of coral sand. See Section 1.4.3.

With the introduction of a semi-dry process during the 1980s the potential production of the plant will increase to 1.28-1.46 x 10^5 tonnes y^{-1} (R. Krishna, pers. comm.) requiring up to 1.75 x 10^5 tonnes y^{-1} carbonate sand. A new cement mill was installed during 1981 and early in 1982 a new barge, incorporating a mounted crane, with a capacity of 1200 tonnes was brought into use.

During the next 25 years, carbonate sand requirements are expected to reach 2.0 x 10^5 tonnes y^{-1} (B.P. Smith, pers. comm.). An average projected requirement of 1.5 x 10^5 tonnes y^{-1} over 25 years totals to 3.75 x 10^6 tonnes. Assuming the same constraints on method and depth of dredging as today, such a quantity of sand would be contained in a reserve of 41 ha with a mean accessible sediment thickness of 7.5m. By the year 2008 the cumulative direct impact of the dredging would affect 2.1% of the total reef area. Of this an estimated 20.5-22.6 ha (assuming the same ratio as 1962-1979) of seagrass would be affected bringing the total (1962-2008) to 14.3-15.5% of the original meadows.

During 1976 Fiji Industries Ltd. made an application to the Fiji Government (Dept. of Lands and Mineral Resources) for a lease to extract sand from the Namuka area (Fig. 1.4.2b and Plate 1.1a). To gain access to this region a channel 20m wide and 1.5km long would be required to link the existing dredge pit, Waiqanaki III, with the narrow lagoon behind Namuka Barrier Reef. There is an extensive seagrass meadow at Namuka estimated to cover 26.8 hectares (Table 1.4.2b).

The lease was not granted on account of the Government's requirement *'for the Company to provide a detailed Environmental Impact Study and Statement of their proposals'*. A draft outline of such a study (see page 224 and Appendix IIa) provided the original conception for this thesis. This work has been carried out in close cooperation with the Fiji Government and Fiji Industries Ltd. and the lease *'over a substantial area of coral in Namuka Harbour'* was approved by the Department of Lands early in 1983 (B.P. Smith, pers. comm.).

1.5. The Research Approach: Perspectives and Constraints.

The location of past, present and potential excavation sites covers some 22km of reef. Description of the hydrography of this considerable area is complicated by the topographical, meteorological and oceanographical heterogeneity of the region.

Possibly the most significant factor accounting for this variability is the location of the Rewa River to the east of Laucala Bay. Not only has this and other smaller rivers played a part in moulding the foundations of the present reefs and passages, but their discharge now accounts for the *oceanographic gradient* which extends through the study area.

The effects of the river discharge into the lagoons and beyond the reefs is not restricted to formation of a surface water layer of reduced salinity. This outflow also carries with it evidence of human activities far removed from the reef: land clearance, highway construction and (within the last five years) the development of the Monosavu Hydroelectric Scheme in central Viti Levu, have contributed a severalfold increase in the suspended sediment load of the Rewa River (Mr. Lloyd Harris, pers. comm.). The sewage and industrial wastes of a city with a population exceeding 150,000 are also considerable. At present most of Suva City sewage is discharged, raw, directly into Suva Harbour. Within the next decade, with the development of a reticulated sewerage system, this will be redirected and discharged via a treatment plant at the head of Laucala Bay.

Combined with these pressures resulting from human activities are the various types of natural destructive agencies to which the biota of coral reefs have been exposed for millenia; tropical cyclones frequently cause severe wave damage, earthquakes have caused extensive reef cracking, tsunamis have hurled massive boulders onto the reef top and flood discharges result in freshwater stress to reef organisms. These processes may equally be considered constructive: material eroded and transported from one region of the reef must ultimately be deposited in another area of accretion.

To these influences, whether natural or due to human activity, the exposure of each reef and lagoon varies. Analysis of these differences and assessment of each area in terms of access, available resource and potential for rehabilitation, is fundamental to the management of sand extraction.

The spatial heterogeneity was a logistical problem severely constraining this fieldwork. For instance it was simply not practical to make frequent visits to the proposed site of future dredging on Namuka Reef. Limitations were imposed by access across the reef (two hours either side of high water), distance (fuel) and wear and tear on the boats and equipment (the lagoons are sufficiently large for the formation of damaging steep choppy seas). Instead, after several daytime visits, a week of more intensive observation was carried out from a camp on Namuka Island and raft moored on the reef.

The problem then lies in deciding how far the results of one short spell of observation may be extrapolated over a longer period. Furthermore, this study requires consideration of two time spans of different orders of magnitude: a geological scale concerned with the formation, erosion and deposition of carbonate sediments and a biological scale concerned with the vastly briefer turnover times of plant and animal communities.

The temporal heterogeneity of hydrographic conditions was always particularly noticeable subsequent to cyclones. In common with the vast majority of reef studies, most of the observations in this study are measurements of prevailing conditions. There is little or no quantitative data on the extreme conditions witnessed during episodic events; cyclones, earthquakes, tsunami, with estimated return periods of 1, 10, even 100 years. This is hardly surprising. The chances of observing a catastrophic event on a reef where a baseline exists are slim. The combined scarcity of workers and unpredictability of occurrence of these events is highly limiting. Neither can the physical aspects be ignored: without the benefit of an array of costly continuous recording instruments, the logistics of making hydrographic observations during a cyclone on an offshore reef present daunting problems.

It is reasonable to assume that the geological and biological framework of the reef is moulded jointly, to varying degrees, by both prevailing and episodic conditions. Intensive periods of observation provide a partial description of the former. Estimation of the latter is a matter of observation and educated guesswork.

2. Oceanography

CHAPTER 2. OCEANOGRAPHY.

Two series of oceanographic data were collected; long-term temperature-salinity information and short-term, detailed studies of the dynamics of important locations.

2.1. Annual Variation in Temperature and Salinity in Laucala Bay; Nukubuco Channel.

Temperature-salinity profiles were determined at monthly intervals at three stations in Laucala Bay, fixed by line transits (Fig. 2.1a). Data were collected from a 4.3m Fyran V-hulled aluminium boat using a Hamon Temperature-Salinity Bridge (Model 602), Nansen reversing bottle with thermometers and secchi disc.

Figures 2.1b and 2.1c show temperature and salinity vs. depth profiles measured at Laucala Bay Station 3, the inner opening of the Nukubuco Channel (Fig. 2.1a), for 12 months commencing August 1979. Profiles for Stations 1 and 2 are contained in Figs. 2.1d and 2.1e. Pertinent meteorologic information is contained in Figures 1.2.1b, 1.2.4b, 1.2.5c and 1.2.6a. The t and s data are set out in two blocks representing the periods of increase and of decrease in water temperature. The profiles may be usefully grouped according to the value of ΔT; the difference between the water temperature at the surface and at 40m (Table 2.1.). Four periods may be identified:

(1) $\Delta T \sim 0$, August to October (Profiles 1, 2, 3). During the period of persistent SE trade winds the water column was well mixed with short-lived temperature stratification limited to the top 10m. Complicated temperature inversions were caused by solar warming of cooler, brackish waters entering the NE corner of Laucala Bay. Salinity increased gradually or stepwise to approximately 20m. From 20m to 50m was generally isohaline.

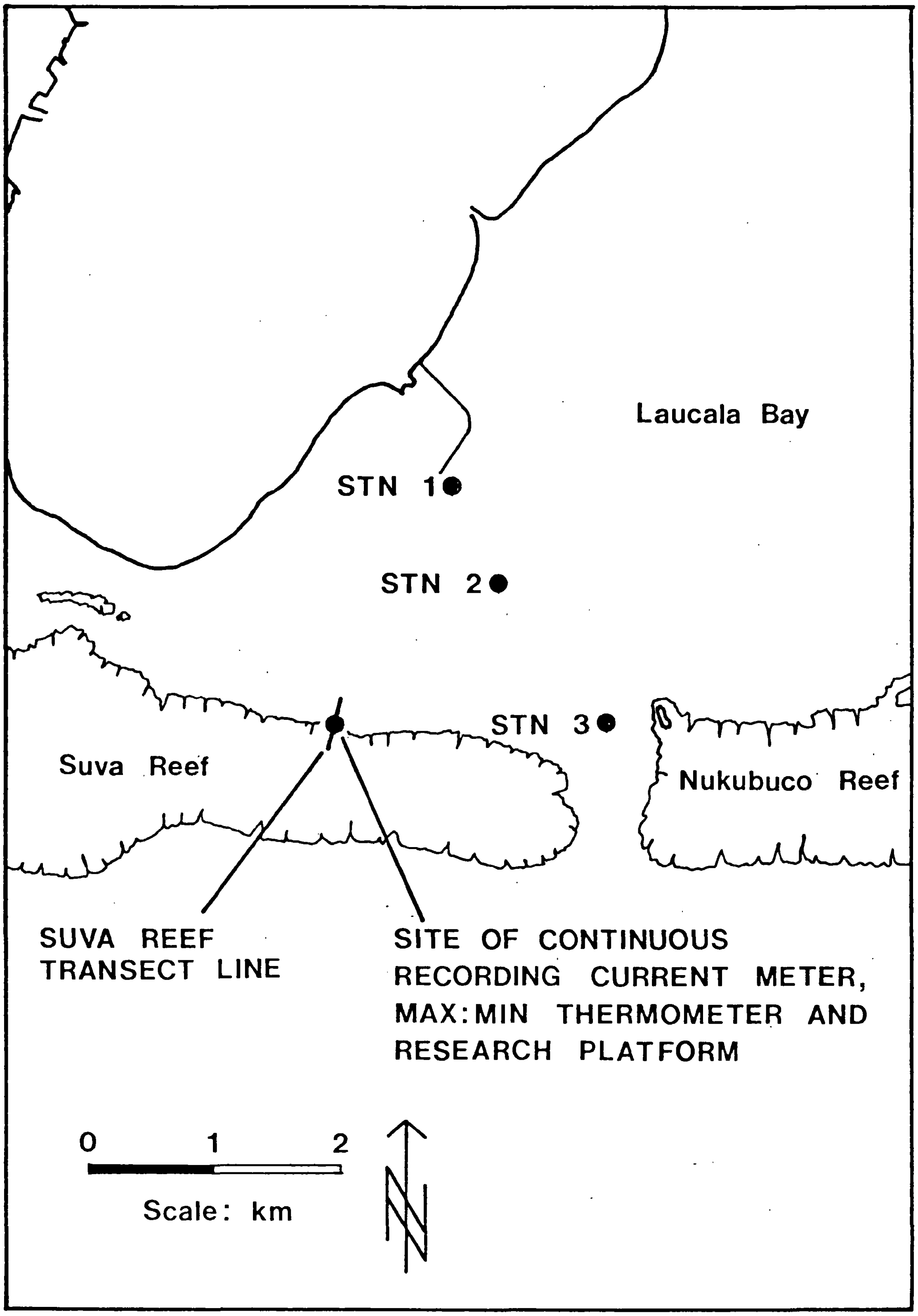


FIGURE 2.1a

Locations of oceanographic stations for monthly observations in Laucala Bay (Stn. 1-3). Location of Suva Reef transect line, current meter, max:min thermometer and research platform.

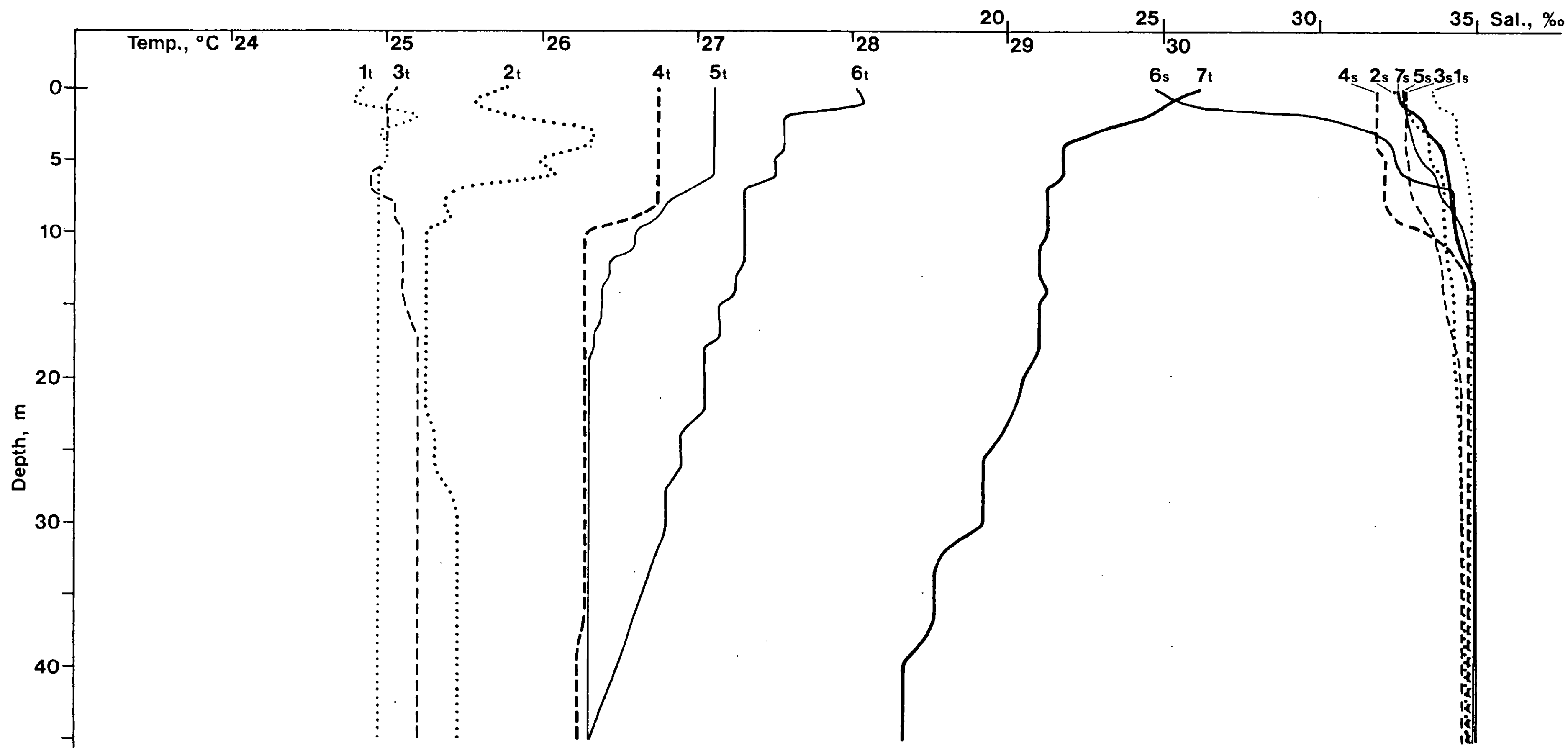


FIGURE 2.1b

Temperature and salinity profiles at Laucala Bay Station 3 in the period August 1979 to March 1980.

1 : 12 Aug 79 2 : 1 Oct 79 3 : 29 Oct 79 4 : 26 Nov 79
5 : 24 Dec 79 6 : 22 Jan 80 7 : 3 Mar 80

t = temperature s = salinity

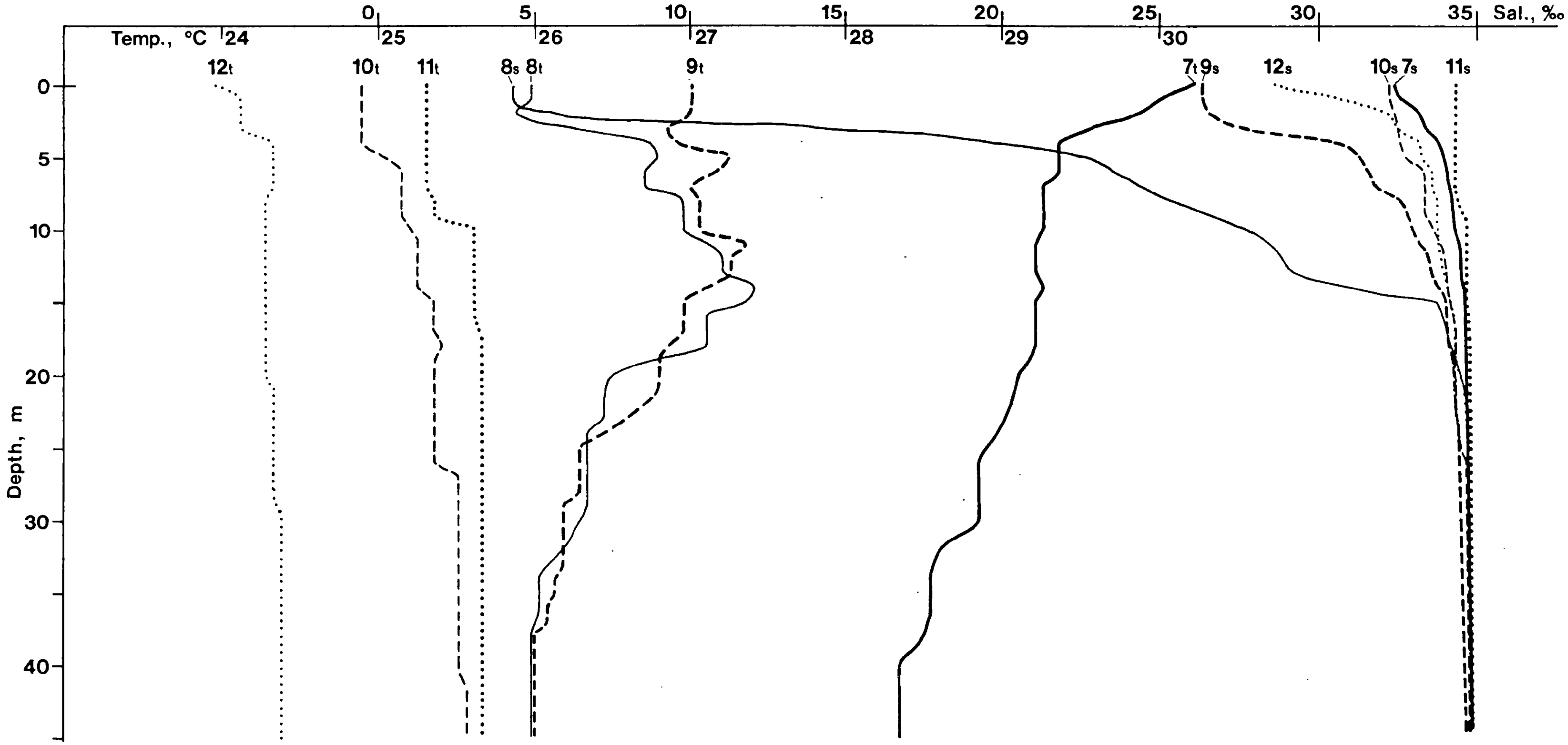


FIGURE 2.1c

Temperature and salinity profiles at Laucala Bay Station 3 in the period March to August 1980.

7 : 3 Mar 80   8 : 5 Apr 80   9 : 14 Apr 80
10 : 15 May 80   11 : 13 Jun 80   12 : 17 Aug 80

t = temperature   s = salinity

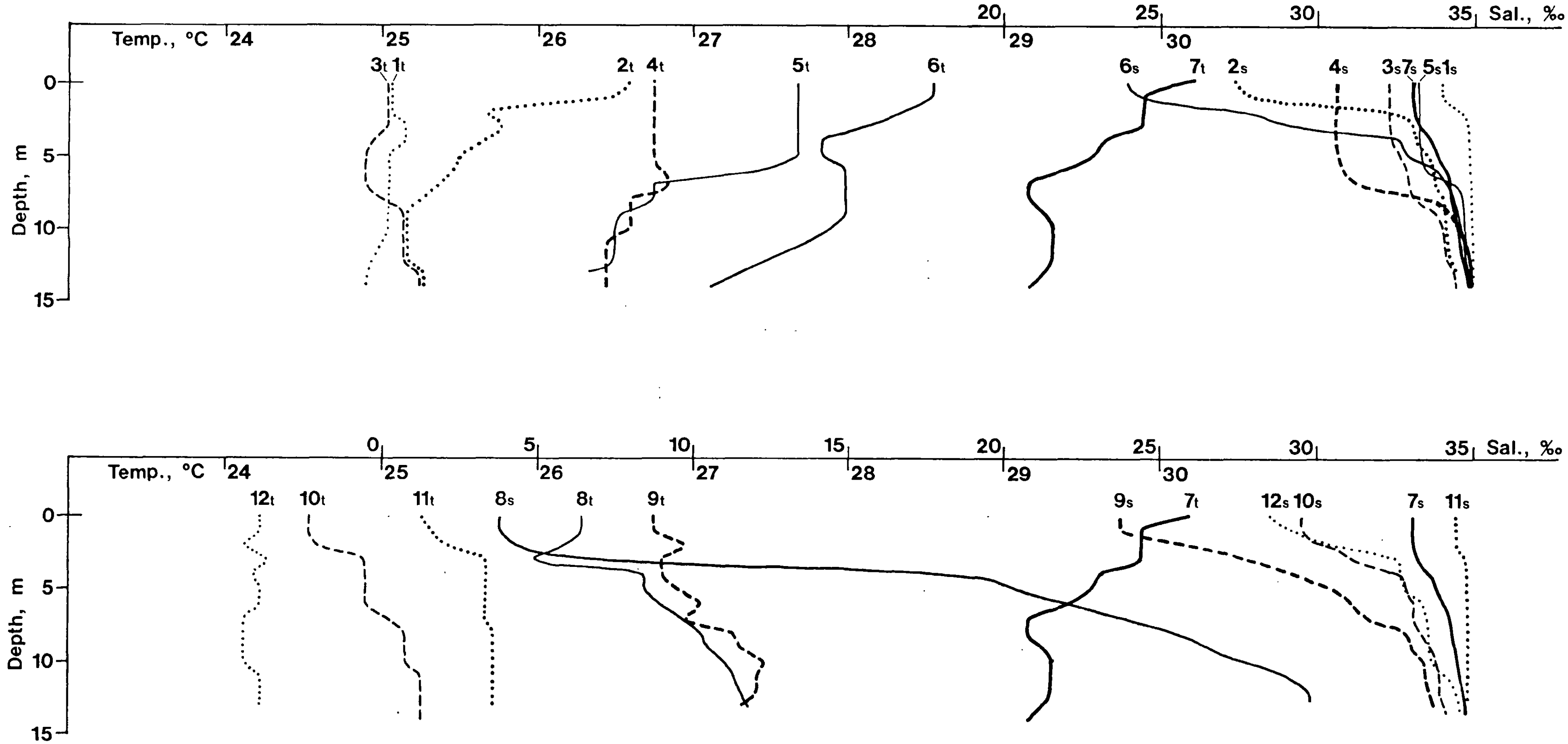


FIGURE 2.1d

Temperature and salinity profiles at Laucala Bay Station 2 in the period August 1979 to August 1980.

1 : 12 Aug 79	2 : 1 Oct 79	3 : 29 Oct 79	4 : 26 Nov 79	5 : 24 Dec 79
6 : 22 Jan 80	7 : 3 Mar 80	8 : 5 Apr 80	9 : 14 Apr 80	10 : 15 May 80
11 : 13 Jun 80	12 : 17 Aug 80			

t = temperature s = salinity

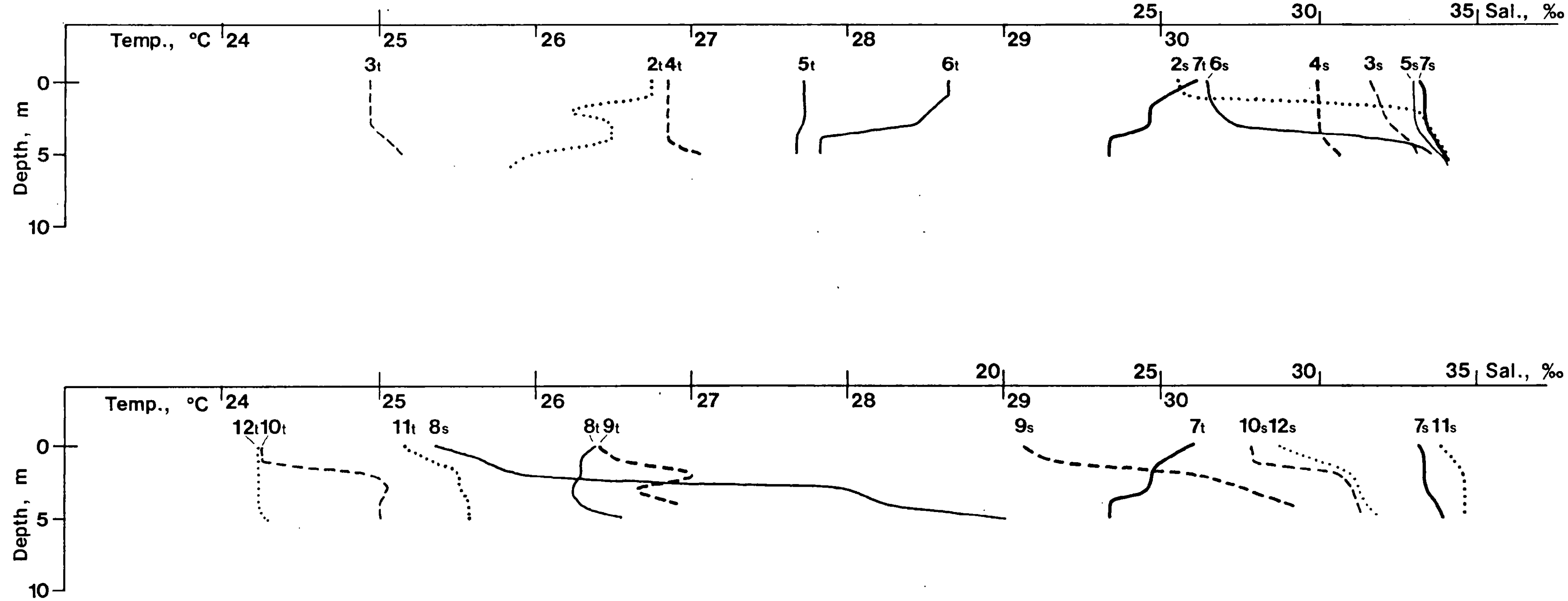


FIGURE 2.1e

Temperature and salinity profiles at Laucala Bay Station 1 in the period August 1979 to August 1980.

1 : 12 Aug 79	2 : 1 Oct 79	3 : 29 Oct 79	4 : 26 Nov 79	5 : 24 Dec 79
6 : 22 Jan 80	7 : 3 Mar 80	8 : 5 Apr 80	9 : 14 Apr 80	10 : 15 May 80
11 : 13 Jun 80	12 : 17 Aug 80			

t = temperature s = salinity

TABLE 2.1. DIFFERENCE IN SEAWATER TEMPERATURE AT SURFACE AND 40m DEPTH, ΔT. LAUCALA BAY STATION 3 (NUKUBUCO CHANNEL). AUGUST 1979 - AUGUST 1980.

Date	Seawater Temperature °C		ΔT °C	Mean ΔT °C
	Surface	40 m		
12/08/79	24.84	24.95	-0.09	
01/10/79	25.77	25.46	+0.31	+0.02
29/10/79	25.05	25.20	-0.15	
26/11/79	26.74	26.23	+0.51	+0.66
24/12/79	27.10	26.28	+0.82	
22/01/80	28.03	26.49	+1.54	
03/03/80	30.24	28.34	+1.90	+1.49
(05/04/80	25.97	25.97	0.00)	
14/04/80	27.00	25.97	+1.03	
15/05/80	24.89	25.51	-0.62	
13/06/80	25.31	25.67	-0.36	-0.46
17/08/80	23.97	24.38	-0.41	

(2) $0 < \Delta T < +1$. November and December (Profiles 4, 5). The reduction in trade winds coupled with increasing air temperature and sunshine hours led to heating of the surface layers and formation of more stable thermoclines at 8-10m. Haloclines were restricted to the upper 12m below which the profile remained isothermal and isohaline.

(3) $\Delta T > 1$. January to April (Profiles 6, 7, 8, 9). This was the hottest part of the year with high daily sunshine and periods of calm. The temperature profiles descended stepwise, cooling with depth to 50m. The rapid rise in temperature of the entire 0-50m layer between late January (#6) and early March (#7) was matched by an equally sudden fall during March brought about by persistent winds and overcast weather. The effects of the major flood consequent to Cyclone *Wally* (see Section 1.2.2.) are shown in profile #8. The cool floodwaters immediately influenced the water column to a depth of 20m producing a 1.5°C temperature inversion and surface salinity of lower than 5°/oo. These waters were also highly turbid with secchi depths of less than 0.1m (Plate 2.1.). Within 10 days the brackish water was mixed to at least 50m depth: the 140480 salinity profile (#9) was displaced to the left and the reduced salinity (34.95°/oo to 34.65°/oo) of the coastal water was noted in the Namuka study (Section 2.2.3.1.).

(4) $-1 < \Delta T < 0$. May to August (Profiles 10, 11, 12). The start of the trade wind season was characterised by reductions in day length, insolation and air temperature. The temperature stratification was inverted with warmer, deeper waters underlying the more rapidly cooling surface layers. Stability was maintained by the salinity stratification.

2.2. Dynamic Oceanography of Backreef Seagrass Zone, Proposed Dredging Site and Recently Excavated Pits.

2.2.1. Introduction.

From early October 1979 a continuous recording current meter was stationed 0.5m above the seabed in the backreef seagrass beds of Suva Reef (Fig. 2.1a and Plate 2.2.1a). Max:Min thermometers were attached to the frame, one buried in the sand (10-20mm), the other 0.7m above. Water depth was 2.1m below chart datum, 3.2m below MSL. The two thermometer records were identical and are shown in Figure 2.2.1b. During the first week, overnight temperature fluctuations of 2.25°C, over 48 hours of 5.75°C and over 7 days of 8.0°C were recorded. Thus the weekly fluctuations of these sublittoral backreef waters exceed the annual fluctuations of offshore waters (Fig. 1.3.2.1b). Current direction was found to be unidirectional, lagoonwards; speed was very variable, some fluctuations related to the tidal cycle, others independent. Further information was required and detailed study of the reef:lagoon interface dynamics were made from a research platform. This project was jointly sponsored by Acrow Pty. Ltd. (scaffolding) and Fiji Industries Ltd. (cement works). The tower Plate 2.2.1b) measured 8.7m high by 2.3m x 2.3m and stood in 3.2m (below MSL) of water. It was situated in the centre of the backreef seagrass beds (Fig. 2.1a and Plate 1.1b.) and was manned continuously for one month.

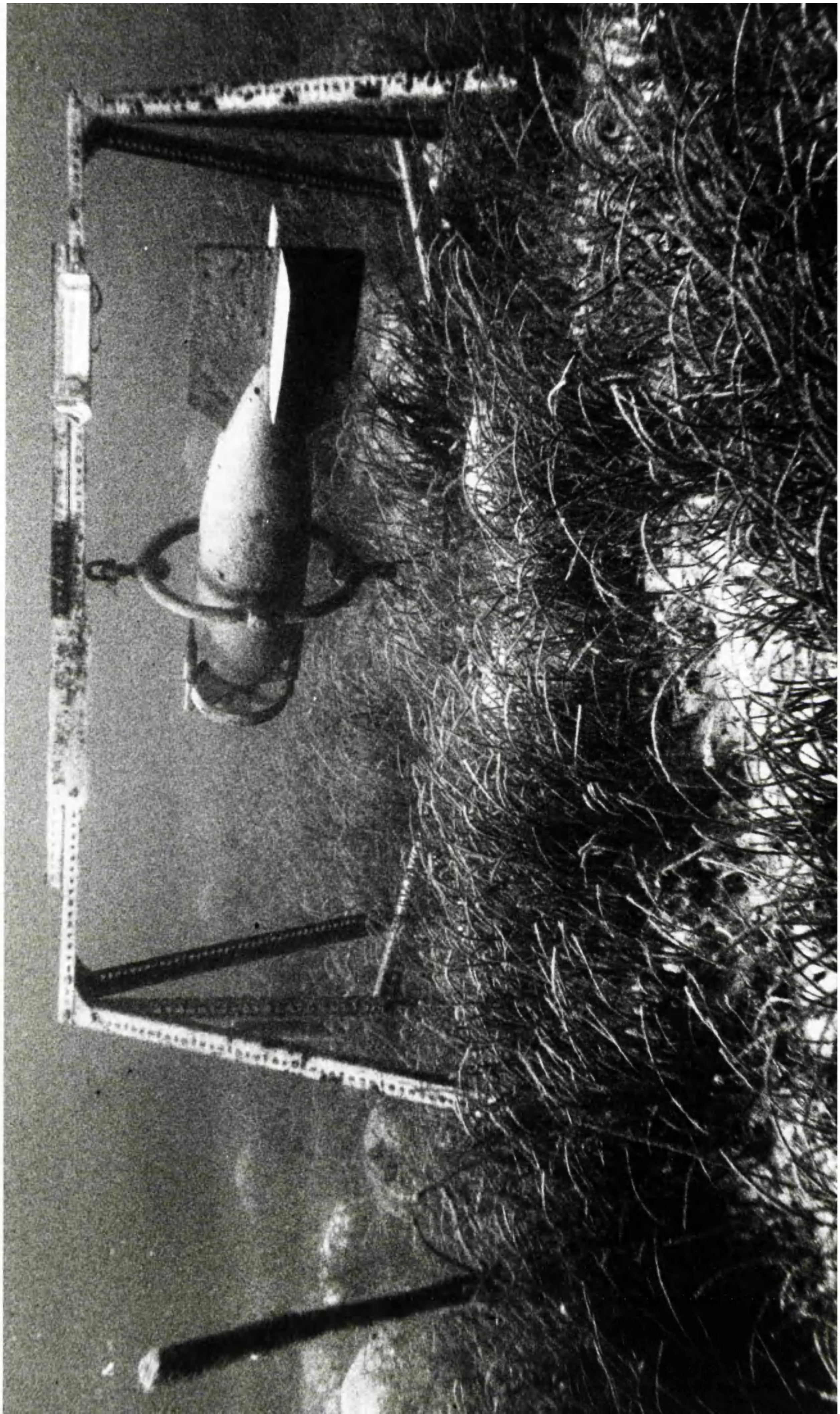
This made possible 12 to 65 hour periods of observation and profiling of temperature, salinity, current speed and direction. Continuous tide gauge (float type) records were also made.

A similar, though less detailed, investigation was carried out on Namuka Reef, a proposed site for future sand extraction, where the reef topography and oceanography differs from the Laucala Bay area. With these baselines, the recently excavated pits on Nukubuco Reef were then investigated

PLATE 2.2.1a

Continuous recording current meter positioned in seagrass meadows (*Syringodium isoetifolium*) at metre 65 along the Suva Reef transect line (see Figures 2.1a and 3.2.1.1a).

Maximum:minimum thermometers attached to top and bottom (buried) of frame. Scale: height of frame (vertical) = 0.7m.



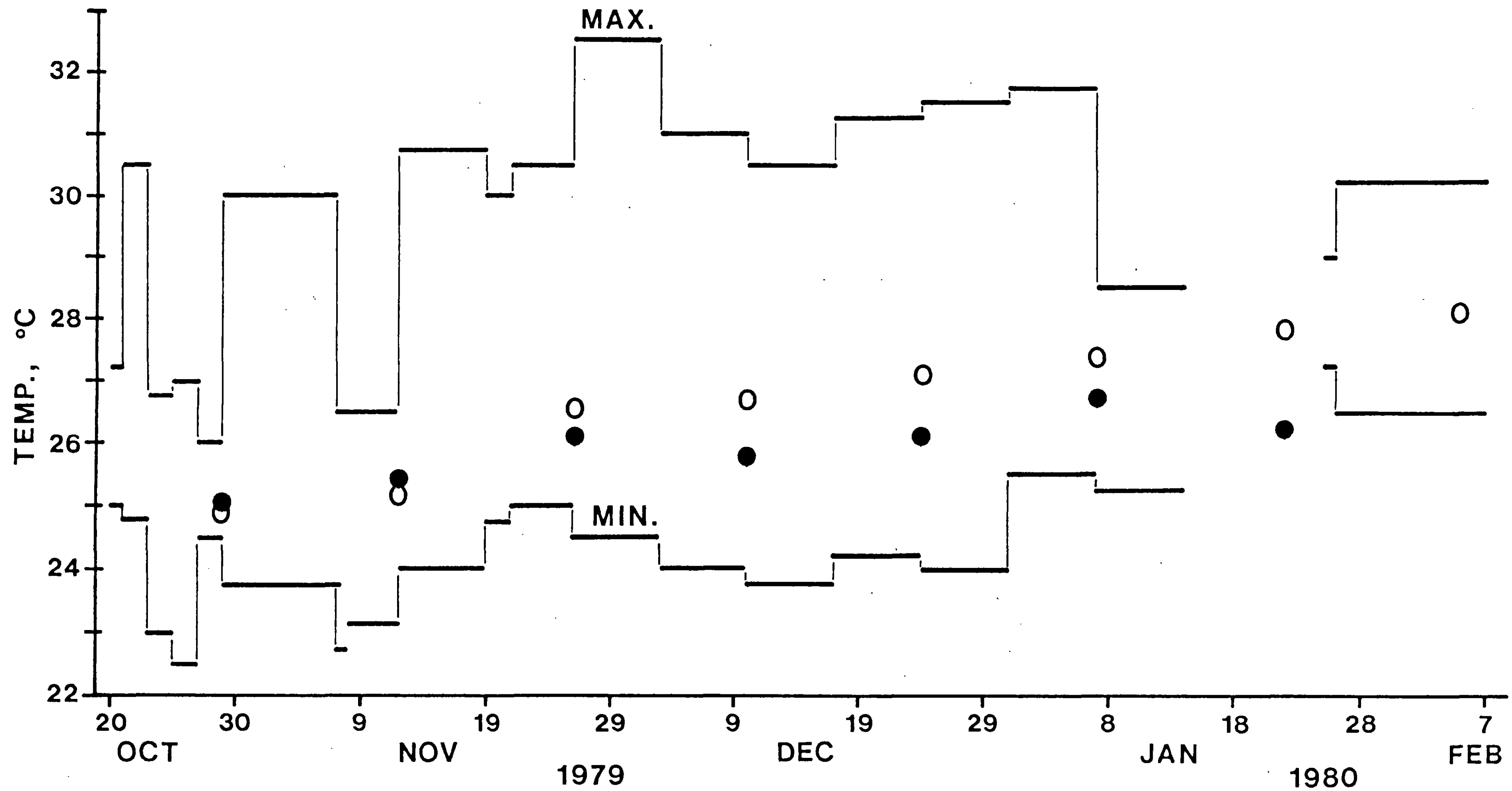


FIGURE 2.2.1b

Maximum : minimum seawater temperatures recorded in the back reef seagrass meadows, Suva Reef.

O surface temperature, Laucala Bay Station 3

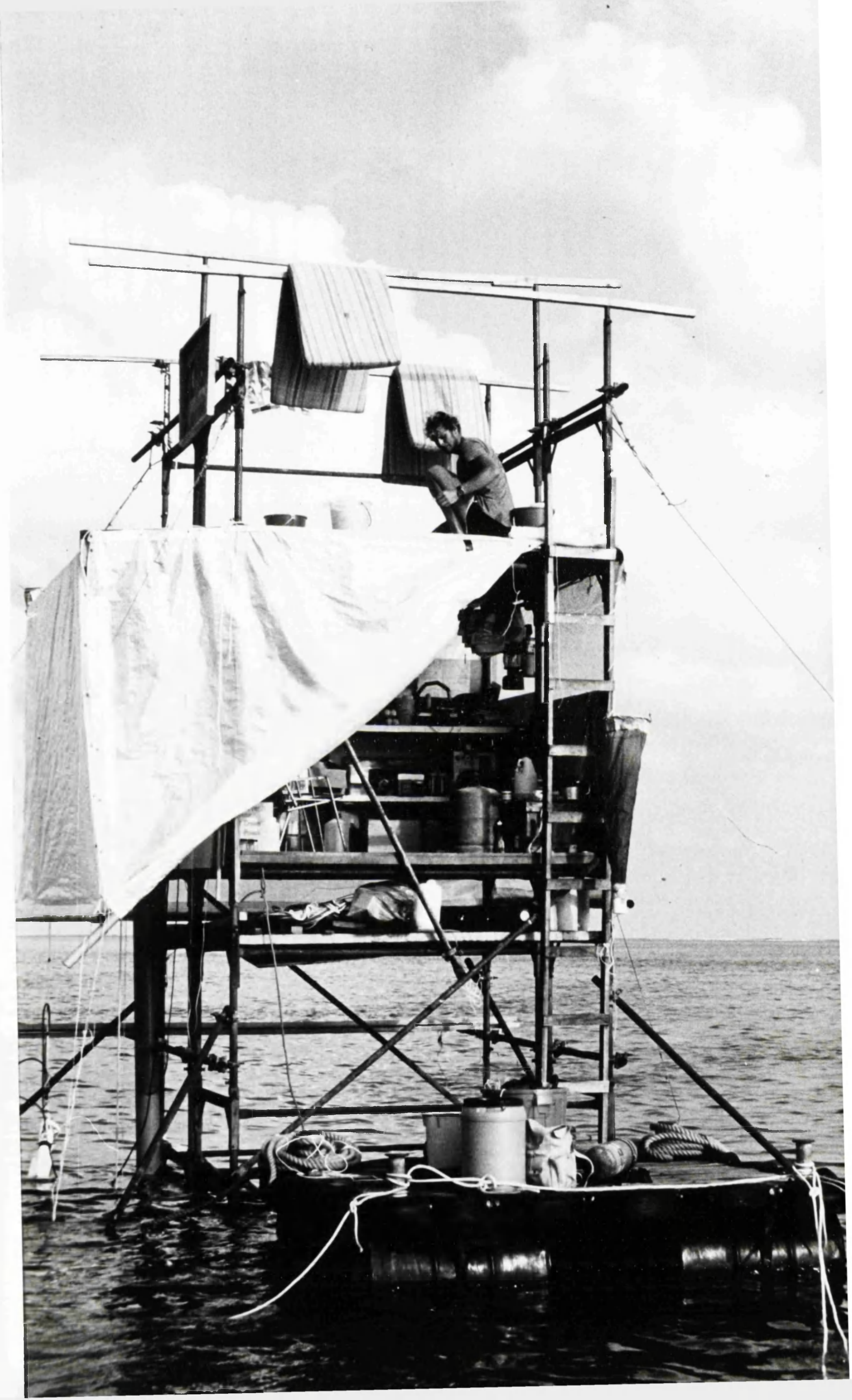
● 40m depth temperature, Laucala Bay Station 3

PLATE 2.2.1b

Research platform constructed on Suva Reef.

Scaffolding tower measured 2.3m long x 2.3m wide x 8.7m high.
Sea bed was 3.2m below MSL.

For location see Figure 2.1a



to assess the effects of changed bathymetry on backreef water movements. Construction of a platform was not feasible in either of these areas (due to remoteness and depth respectively) and sampling was carried out from a moored raft (Plate 1.1a and 1.1b).

At all locations temperature and salinity data were collected using a Hamon Temperature-Salinity Bridge (Model 602), current profiling using a Toho Dentan Current Meter (Model CM 2) and continuous current measurement (0.5m above sea bed) using an Ono's Self-Recording Current Meter.

2.2.2. Suva Reef: Control Site in Backreef Seagrass Zone.

The physical oceanography of this backreef area involves two readily distinguishable water masses:

(1) Supra-reefal marine incursive waters (MIW): the wave-driven input of offshore waters flowing across the reef flat into the lagoon. These cannot be considered oceanic waters on account of the admixture of freshwater, particularly from the Rewa discharge, which extends, in the upper water layers, many kilometres outside of the reef. The salinity of the MIW typically ranges from 34.7-35.0°/oo with secchi depths of 10-15m.

(2) Lagoonal brackish surface waters (LSW): highly variable in characteristics, composed partly of the discharge from the Rewa and other rivers. Frequently very turbid with secchi depths of 1-5m, rich in nutrients and a salinity of 1-34°/oo.

These water masses meet at a convergence located, under prevailing conditions, along the backreef seagrass flats, the zone suitable for coral sand extraction. The convergent 'front' is marked by a line of floating debris, a change in water colour and often a change in surface characteristics (the front actually reflects waves, setting up clapotis in the MIW). It is thus a hydrographic indicator of the relative positions of the water masses. Furthermore, the direction of movement of the front, lagoonwards

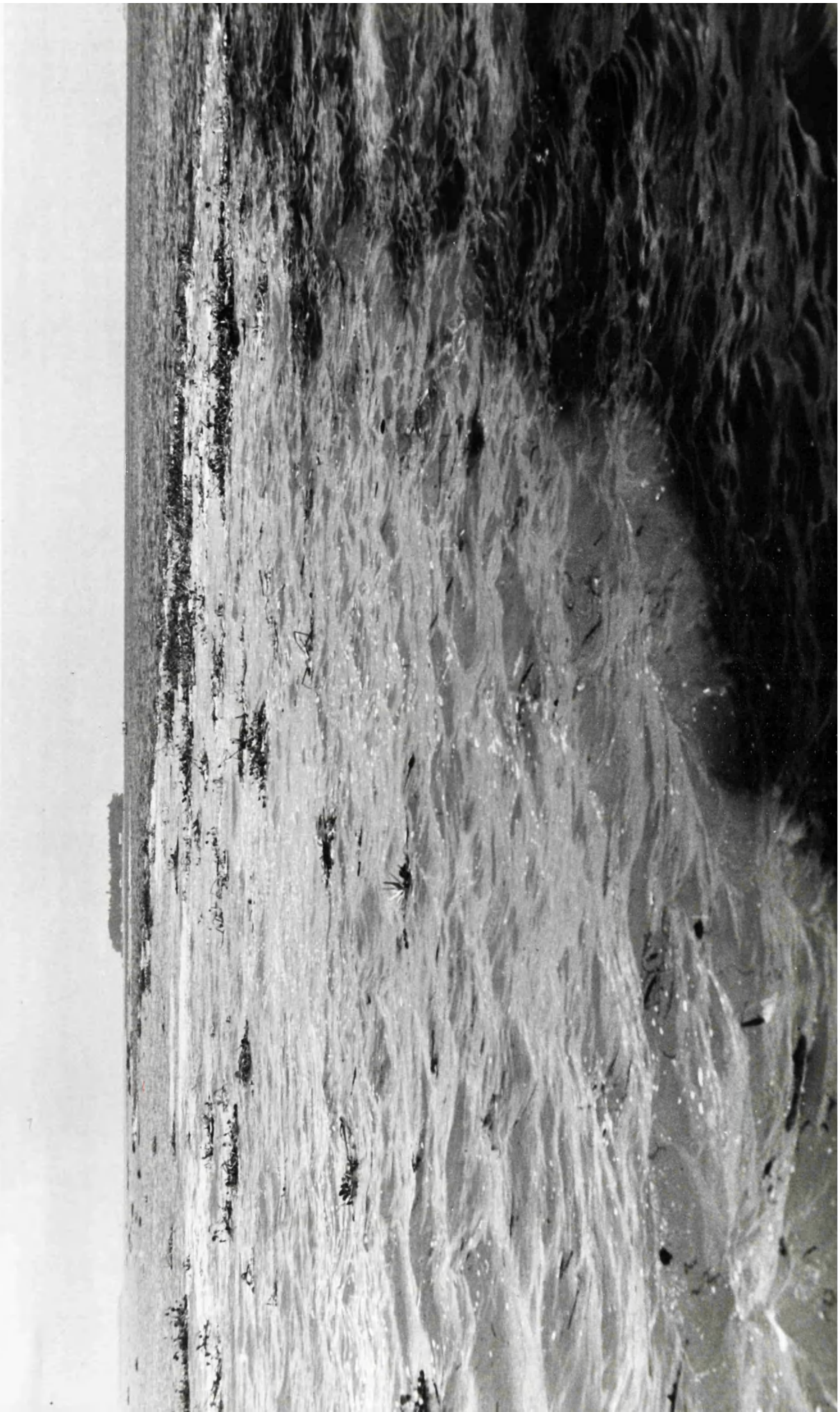
PLATE 2.2.2a

Convergent front between the Lagoonal Brackish Surface Water (LSW) mass (left) and the Marine Incursive Water (MIW) mass (right).

Location: Nukubuco Reef, over back reef seagrass meadows (visible below MIW) between Nukubuco Island and dredge pit Nukubuco II (see Figure 1.4.2b). Looking east towards Nukulau Island.

Photographed on 5 April 1980 during the period of peak discharge from the Rewa River following Cyclone *Wally* (see Sections 1.2.4 and 1.2.5).

LSW characterized by high turbidity and salinity less than $1^{o}/_{oo}$. Floating mats of water hyacinth, carried down from the river, are concentrated along convergence.



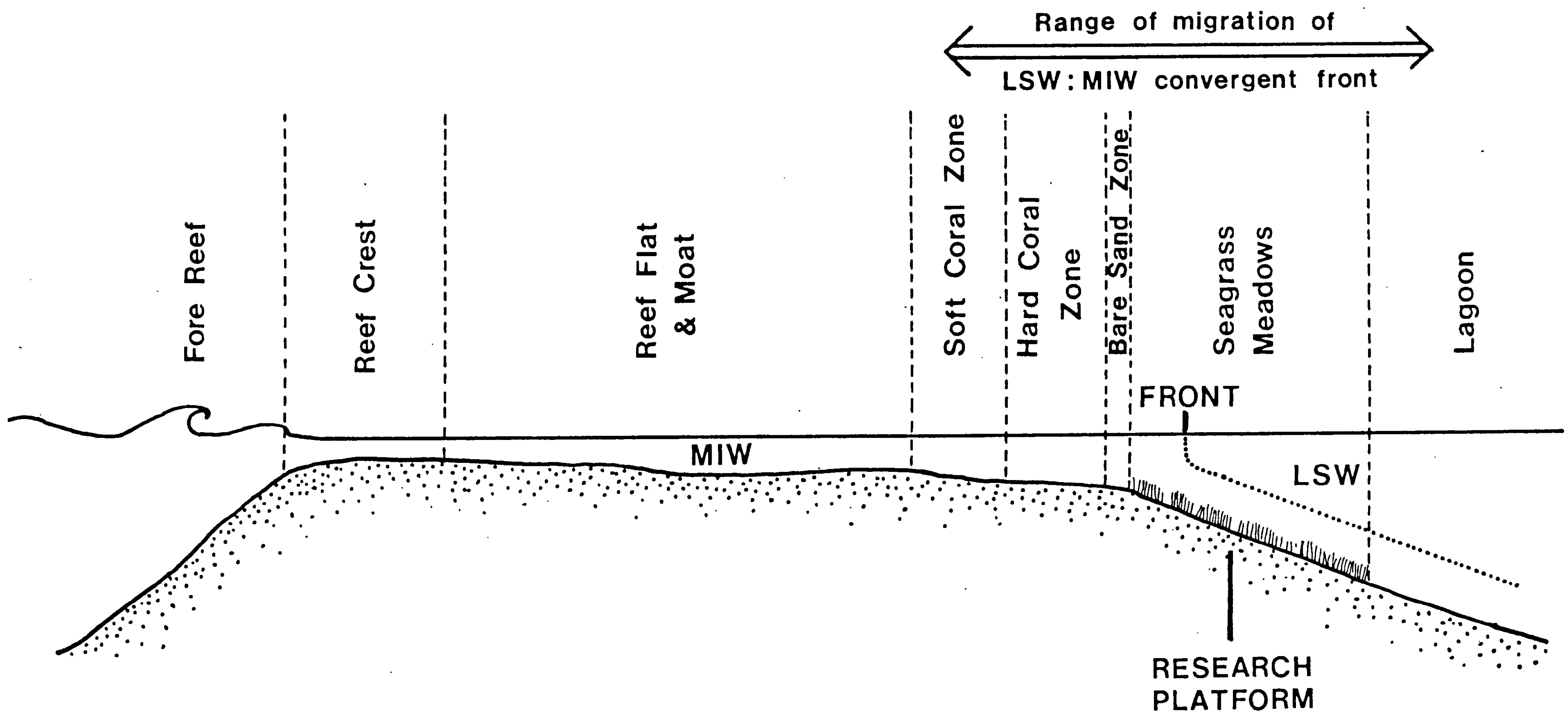


FIGURE 2.2.2.a

Schematic cross-section through Suva Barrier Reef showing major reef zones, research platform location and range of migration of the LSW:MIW convergent front.

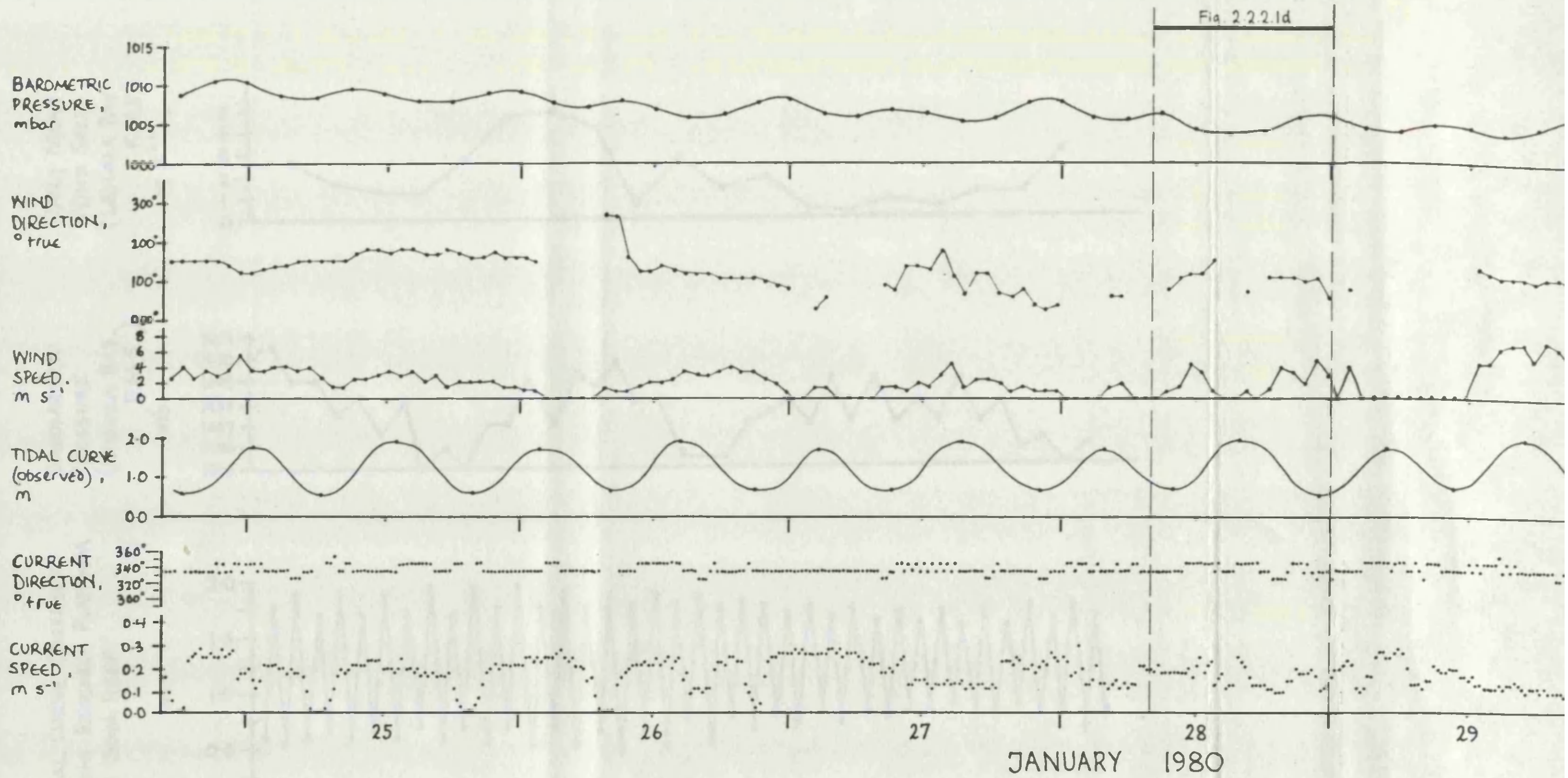
or reefwards, is a sensitive guide to the changing equilibrium between the water masses. The research platform was situated in the centre of the backreef seagrass zone such that during any period of observation the LSW:MIW boundary (marked by the front) lay sometimes reefward, sometimes lagoonwards of the platform (Fig. 2.2.2a).

2.2.2.1. Results.

Observations from the platform were made from 28th January to 8th February, 1980. During this period, offshore seawater temperature fluctuated from 27.5-28.5°C (Fig. 1.3.2.1b). Sunshine hours (Fig. 1.2.6a) were moderate, averaging 6.2h day^{-1}. Rainfall was low, no daily total at Laucala Bay exceeding 25mm (Fig. 1.2.4b) and no floods were recorded in the Rewa (Fig. 1.2.5b). Wind speed and direction is shown in Figure 2.2.2.1b. The first week was characterized by E-SE winds of 4-6m s^{-1} often persisting throughout the night. There was one period of fresher E-NE winds (3m s^{-1}) on 3rd February. Winds during the second week were very light and restricted to daytime onshore breezes.

A continuous tide record was obtained (Fig. 2.2.2.1b). The low tide at the platform site lagged behind the Suva Harbour Prediction by up to 50 minutes (Fig. 2.2.2.1c) with a mean of 18 minutes. The high tide lag averaged 7 minutes. Maximum lag was observed on 7th and 9th February, coincident with neap tides, low wind speed and low reeftop current speed. Although hydrographic observations covered both spring and neap tides, on account of the annual pattern of tides (Section 1.3.1.), the lowest daytime ebb was only 0.6m (cf. MLWS: 0.38m).

The observations of 28th January covered a spring tide cycle, with low water (0.6m) falling at 1000, high morning insolation and light variable winds from the E-SSE (Fig. 2.2.2.1d). At low water the front lay reefwards of the platform: brackish LSW (29°/oo) overlay MIW (34.7°/oo). The water



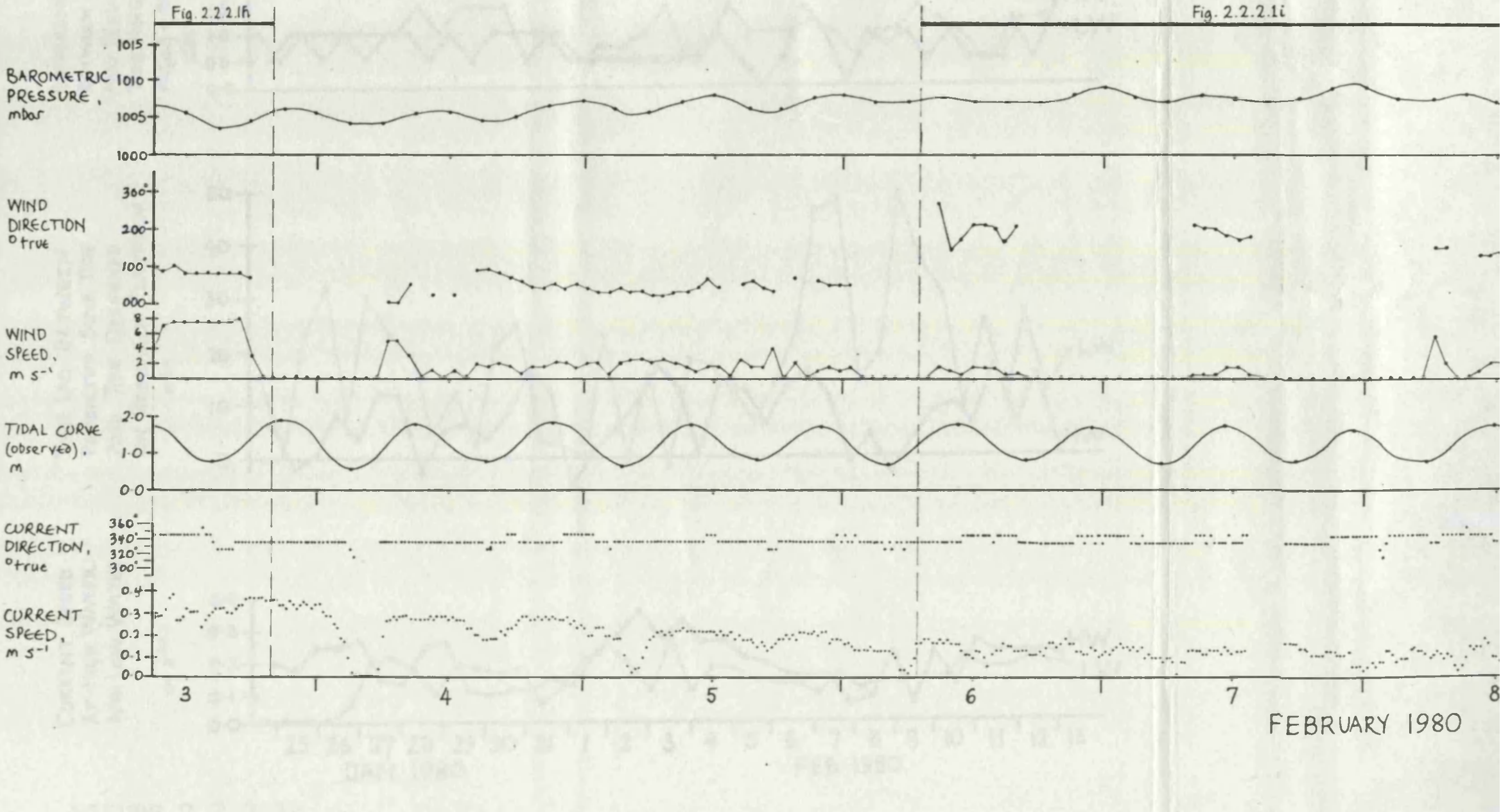


FIGURE 2.2.2.1b

Current meter and tide gauge records from the research platform on Suva Reef in the per
Wind speed and direction and barometric pressure from FMS Laucala Bay Station.

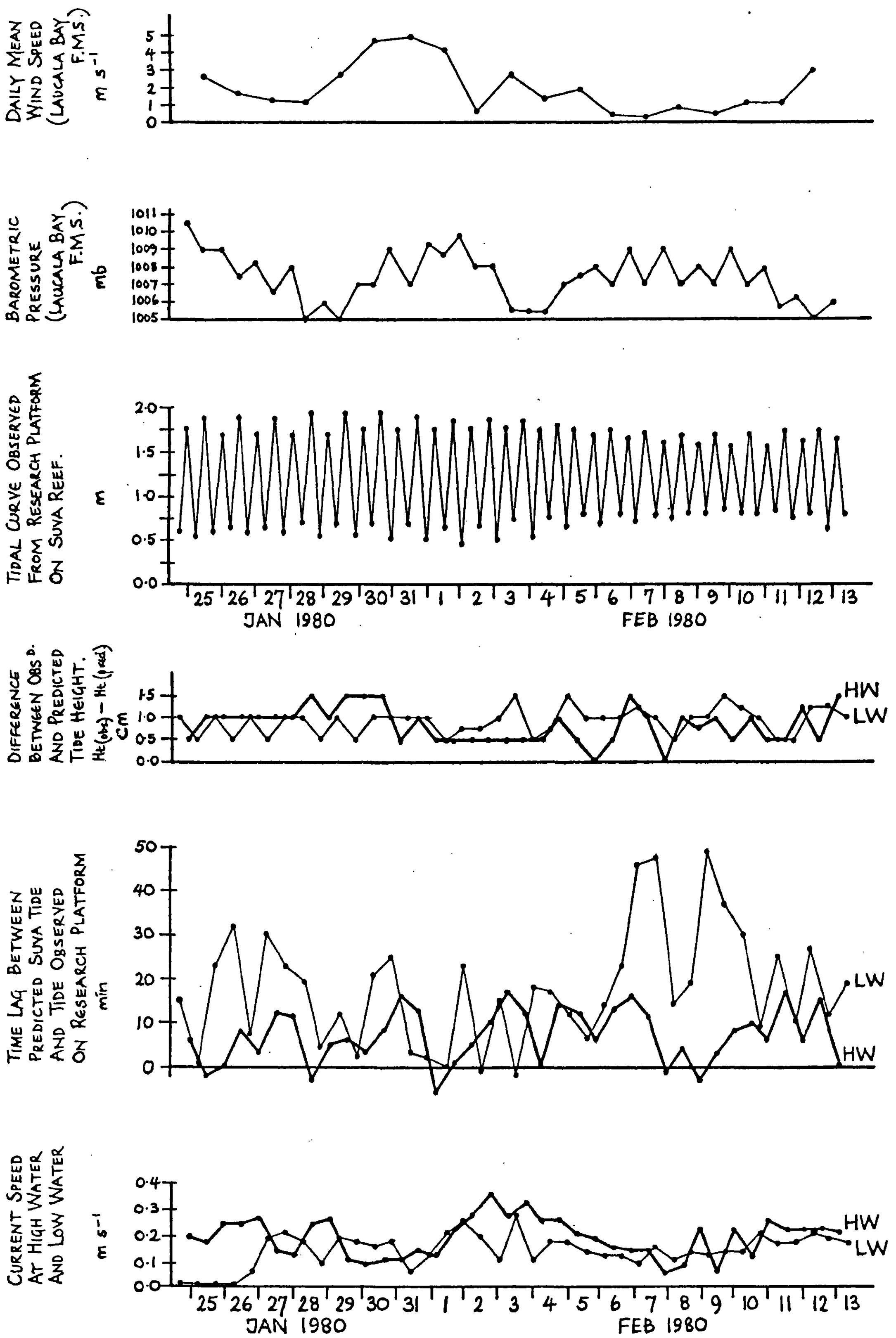


FIGURE 2.2.2.1c

i) Daily mean wind speed
ii) Barometric pressure; 0000 and 1200 obsns.
iii) Tide gauge record from the Suva Reef research platform.
iv) Difference between observed and predicted (Suva) tide heights.
v) Time lag between the predicted Suva low water (Admiralty Tide Tables, Vol. III, 1980) and the observed low water.
vi) Current speed at times of observed high and low water.

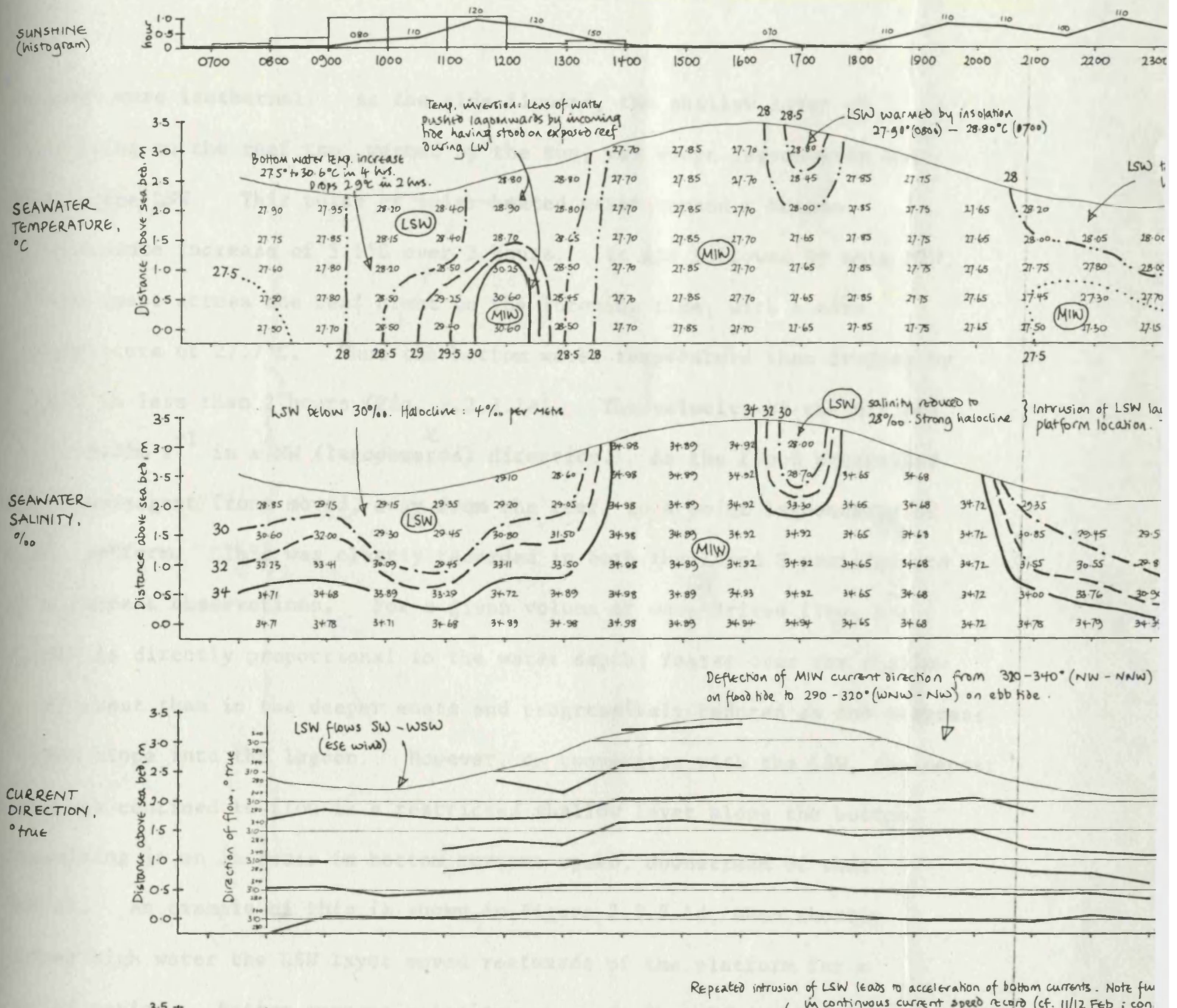


FIGURE 2.2.2.1d

Hydrographic observations at the research platform site, Suva Reef, in the period 0800 to 2400, 28 January 1980.

masses were isothermal. As the tide flooded, the shallow layer of MIW lying on the reef top, warmed by the sun, was swept lagoonwards and below the LSW. This pulse of solar-heated water caused a bottom temperature increase of 3.1°C over 3 hours. It was followed by more MIW, newly swept across the reef crest on the incoming tide, with a core temperature of 27.7°C. Thus the bottom water temperature then dropped by 2.9°C in less than 2 hours (Fig. 2.2.2.1e). The velocity of the MIW was 0.12-0.25m s^{-1} in a NW (lagoonwards) direction. As the flood progressed the convergent front moved, away from the reef, to a point lagoonwards of the platform. This was clearly recorded in both the T and S profiles and the current observations. For a given volume of wave-driven flow, the speed is directly proportional to the water depth; faster over the shallow reef crest than in the deeper moats and progressively reduced as the seagrass flats slope into the lagoon. However, on converging with the LSW, the denser MIW was confined to flow in a restricted shallow layer along the bottom, resulting in an increase in bottom current speed, downstream of that point. An example of this is shown in Figure 2.2.2.1d, when shortly after high water the LSW layer moved reefwards of the platform for a brief period. Bottom current velocity was approximately doubled during this and other similar 'intrusions', represented by peaks on the continuous current meter record. As the tide ebbed, MIW occupied the whole column at the measuring site; flow in this unrestricted layer was in a WNW direction, velocity increasing from 0.5m s^{-1} close to the sea bed to 2.0m s^{-1} at the surface. The LSW gradually moved reefwards, the front passing the platform at mid-ebb. Since the LSW periodically lay lagoonwards of the platform (particularly over the high water period) when measurements of water characteristics and movements could not be obtained, the profiles are incomplete. However, during the low water periods, significant movement

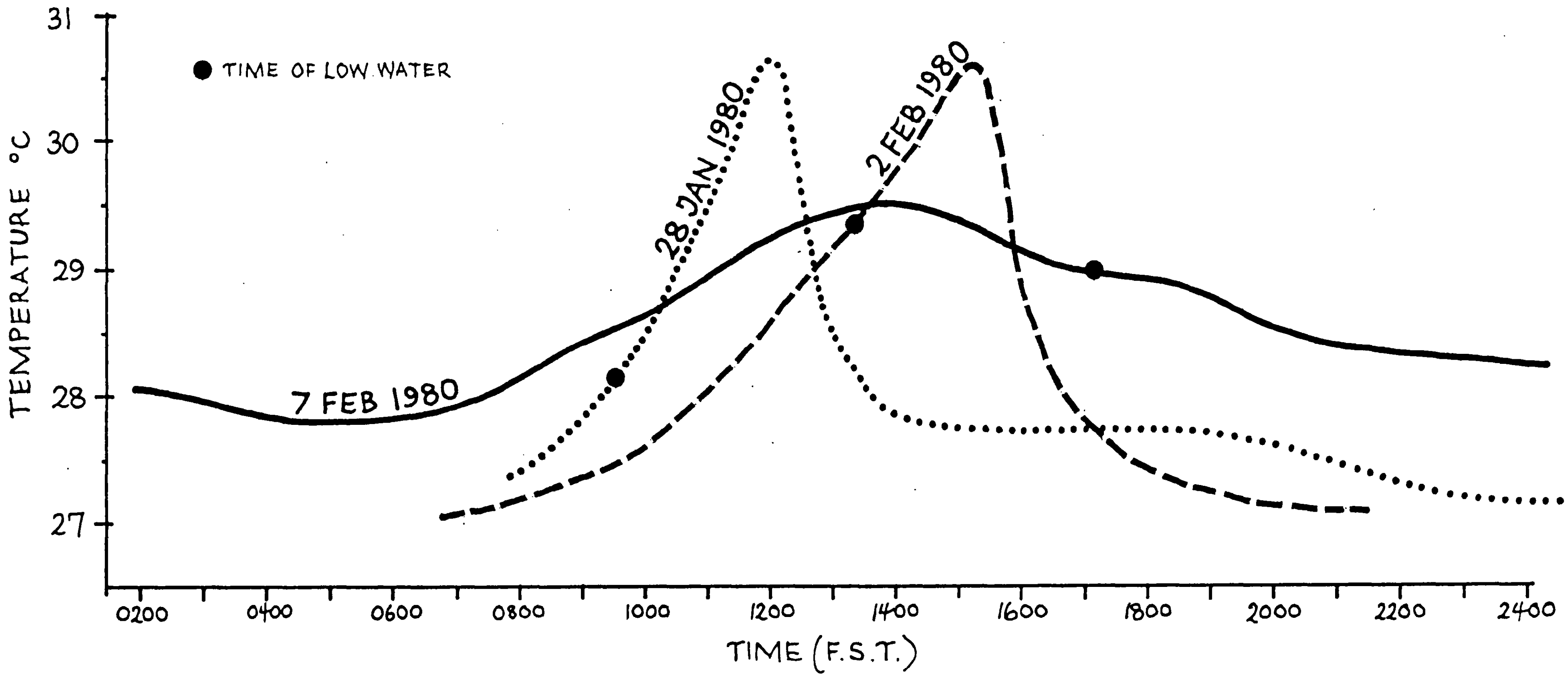


FIGURE 2.2.2.1e

Relationship between fluctuations in bottom water temperature and the time of low water. Research platform, Suva Reef; 28 January, 2 and 7 February 1980.

was observed in a SSW-SW direction with velocities reaching 0.1m s^{-1}.

The second set of observations (1st February) were taken after an interval of 72 hours characterized by continuous SE winds of 4-6m s^{-1}. The halocline in the bay persisted and the T/S:time series (Fig. 2.2.2.1f) is essentially similar to 28th January. Bottom water temperature increased 2.35°C during the early flood, dropping 2.70°C within less than an hour at mid-flood. Flow in the MIW was maintained throughout the low water period and irregular peaks seen on the continuous current record during the flood mark the periodic intrusion of the LSW layer over the meter site.

On the following day, 2nd February (Fig. 2.2.2.1g), winds were light SSE, insolation high, low water at 1331 (0.6m). Overnight between 1st and 2nd February, the character of the LSW changed, with a reduction in surface salinity from 29°/oo to 19°/oo, the two metre deep top layer containing 30-40% Rewa discharge. Except for one brief period during the ebb, the brackish water layer remained well up against the backreef throughout the day. The MIW, forming a thin bottom layer, showed a temperature increase from 27.05°C at high water to 30.5°C at low water, rapidly followed by a drop of 2.2°C during the second hour of the flood (Fig. 2.2.2.1e). Surface heating of the LSW in the middle of the day led to the formation of a shallow diurnal thermocline. Water flowing across the bay later in the afternoon, both cooler and fresher due to river discharge at low water, caused a temperature inversion over this stratification. Maximum current speed in the MIW was recorded on the flood tide (Fig. 2.2.2.1b), reaching 0.45m s^{-1} and exceeding 0.35m s^{-1} for the 3 hours before high water. Bottom flow was remarkably steady by comparison to the 1st February record: the only short-period (less than 1 hour) fluctuation occurred during the ebb when the front moved briefly lagoonwards of the platform, with resulting reduction in current speed. Over low water

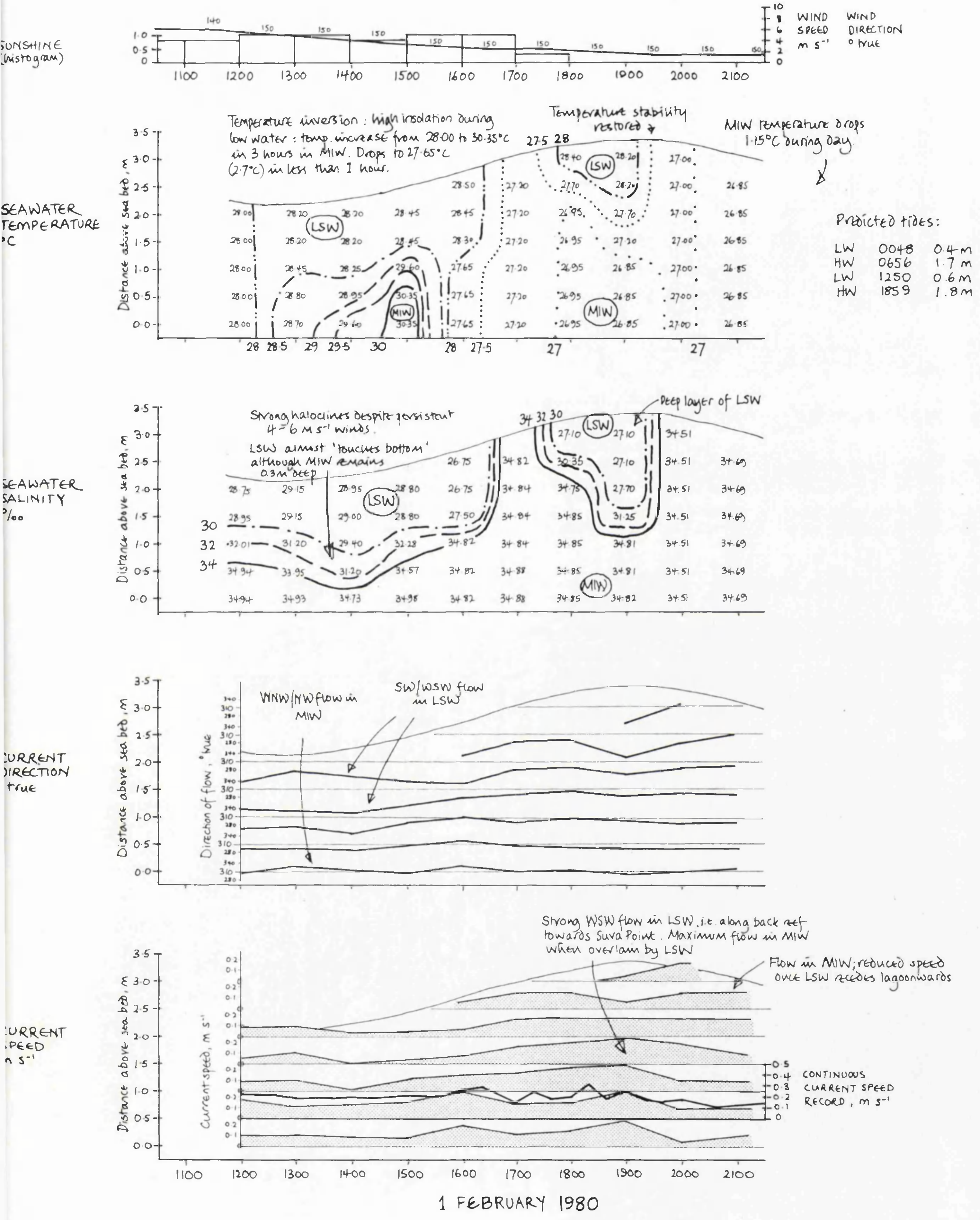


FIGURE 2.2.2.1f

Hydrographic observations at the research platform site, Suva Reef, in the period 1200 to 2100, 1 February 1980.

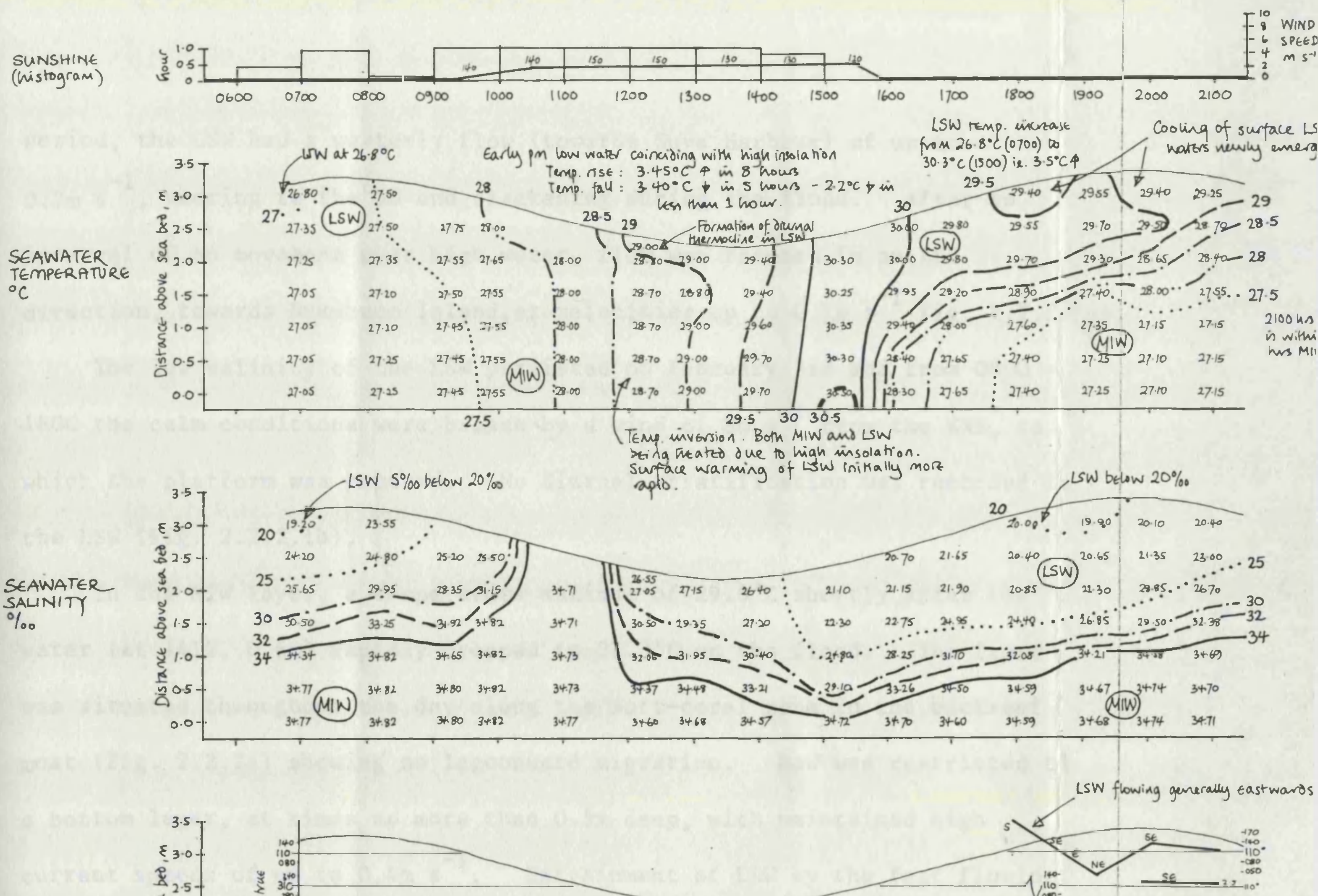


FIGURE 2.2.2.1g

Hydrographic observations at the research platform site, Suva Reef, in the period 0700 to 2100, 2 February 1980.

period, the LSW had a westerly flow (towards Suva Harbour) of up to 0.2m s^{-1}, veering to the SW and slackening during the flood. After an interval of no movement over high water, flow was resumed in an ESE direction, towards Nukubuco Island, at velocities up to 0.1m s^{-1} Fig. 2.2.2.1g).

The low salinity of the LSW persisted on February 3rd and from 0800 - 1800 the calm conditions were broken by a wind of 8m s^{-1} from the ENE, to which the platform was exposed. No diurnal stratification was recorded in the LSW (Fig. 2.2.2.1h).

In the MIW layer, a temperature maximum of 29.6°C shortly after low water (at 1412, 0.6m) rapidly dropped to 27.3°C on the flood. The front was situated throughout the day along the soft-coral zone in the backreef moat (Fig. 2.2.2a) showing no lagoonward migration. MIW was restricted to a bottom layer, at times no more than 0.5m deep, with maintained high current speeds of up to 0.4m s^{-1}. Entrainment of LSW by the fast flowing MIW caused a reduction in bottom salinity to below 34°/oo at the beginning of the flood.

As on February 2nd, WSW flow of 0.05-0.20m s^{-1} was observed in the LSW 3 hours either side of low water.

The longest and final period of oceanographic profiling was carried out from 6-8 February (Fig. 2.2.2.1b). In contrast to the meteorological and oceanographical conditions prevailing during the previous observations, this period was characterised by neap tides, low water falling between 1600 and 1800, LSW salinity exceeding 29°/oo and winds slight from the SSW-SE.

The isohalines (Fig. 2.2.2.1i) showed a recurrent semi-diurnal pattern. A layer of LSW, 1.5-2.0m deep (at the platform site) at low water, slowly thinned as it receded lagoonwards during the flood tide. The front passed below the platform shortly after high water and returned,

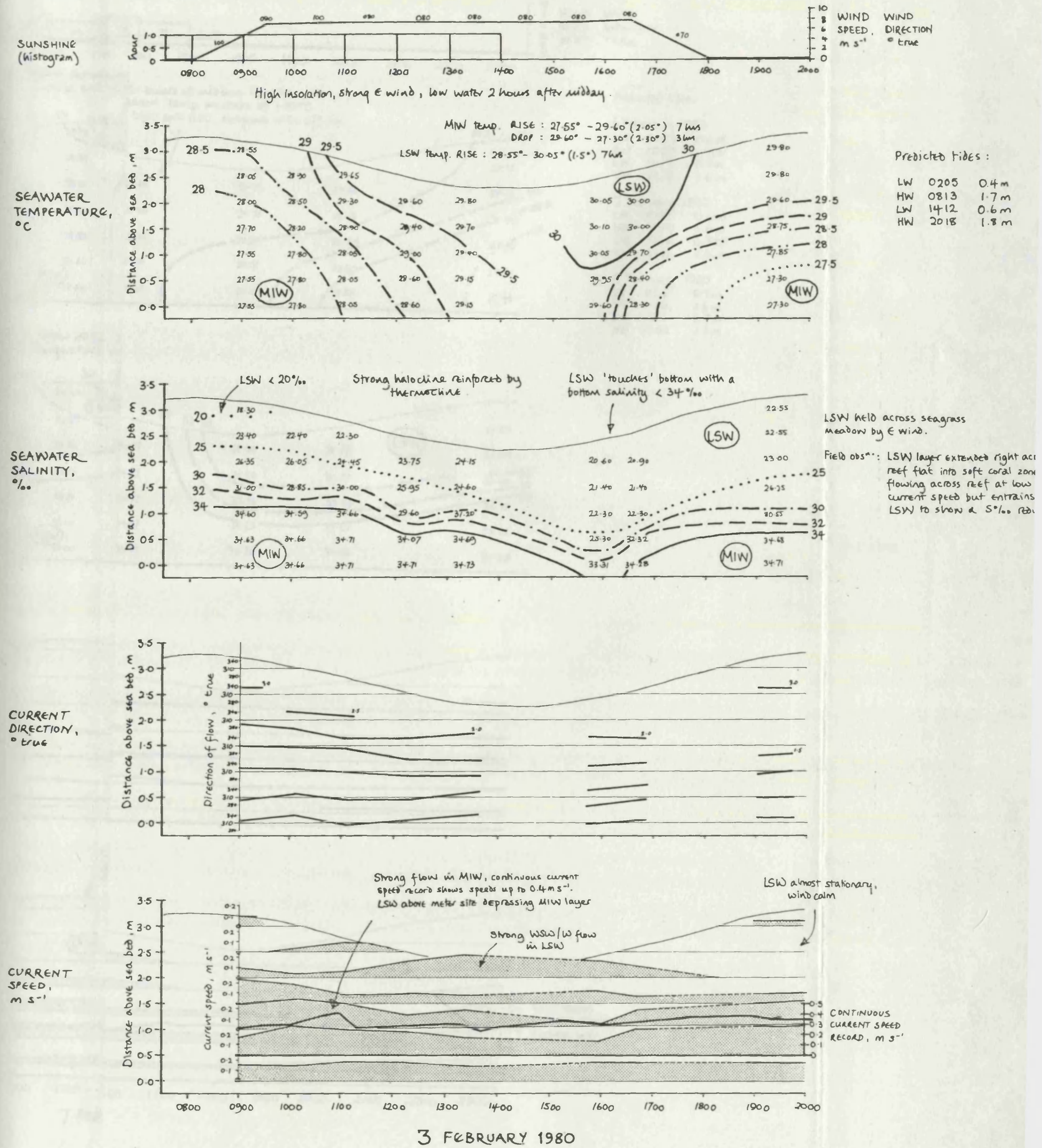


FIGURE 2.2.2.1h

Hydrographic observations at the research platform site, Suva Reef, in the period 0900 to 2000, 3 February 1980.

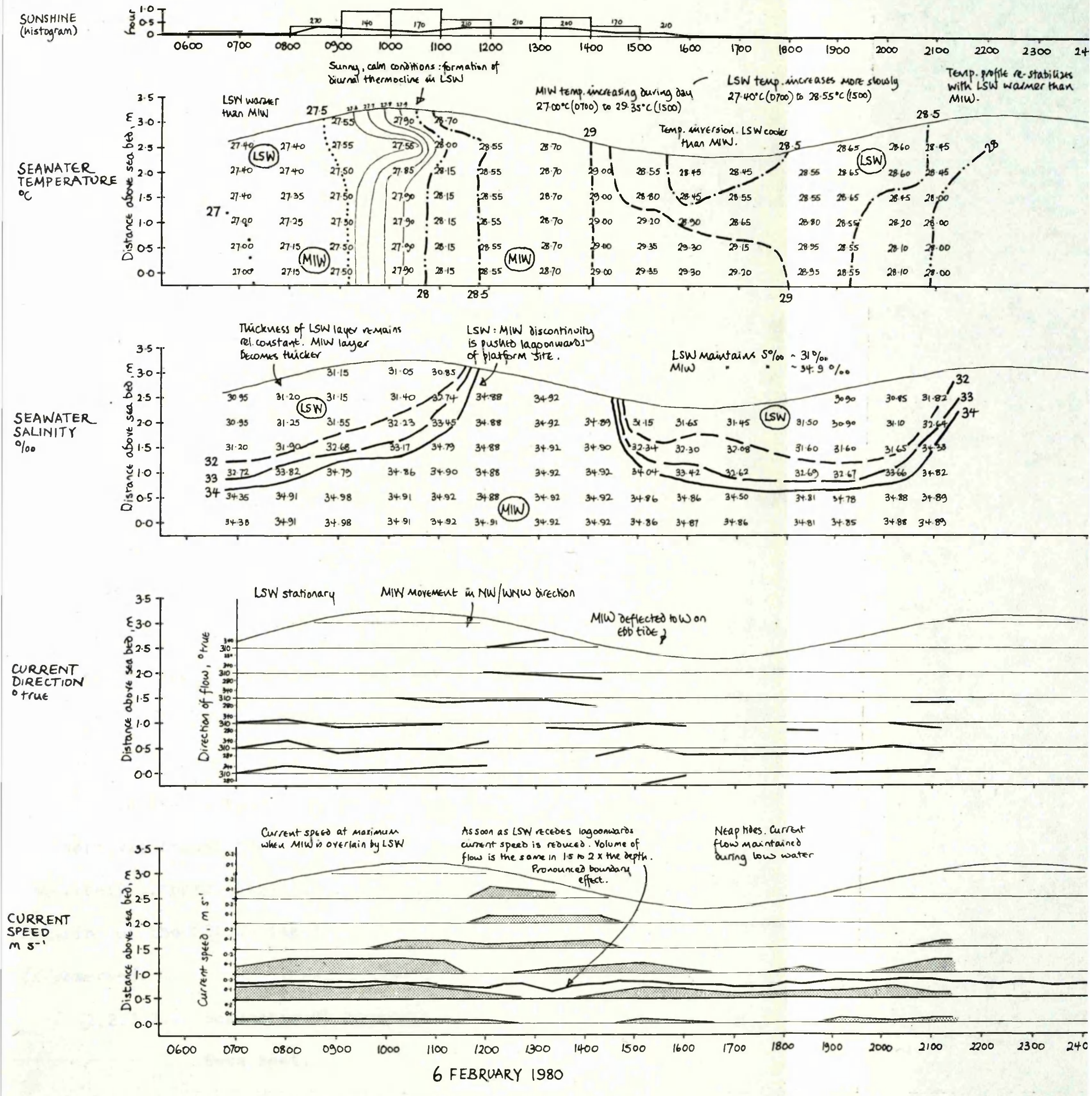
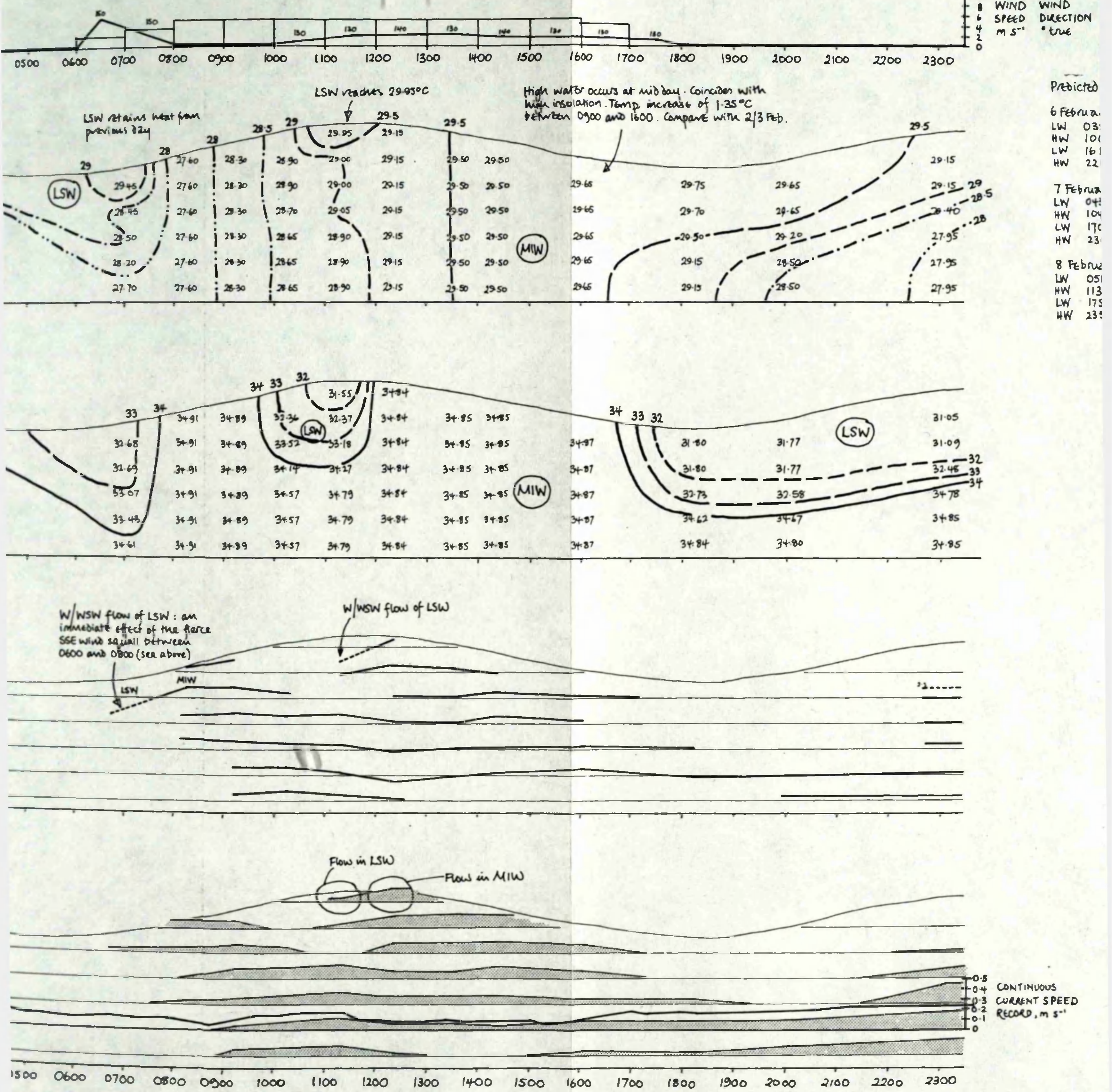


FIGURE 2.2.2.1i

Hydrographic observations at the research platform site, Suva Reef, in the period 0700,



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moving reefwards, 2-3 hours later, during the ebb tide.

Temperature changes followed a diurnal cycle. With calm conditions and high insolation a shallow (0.5m) thermocline was formed in the LSW by mid-morning (Fig. 2.2.2.1i). This was broken down later in the day by the cooling effect of waters discharged from the Rewa during the ebb tide. In the MIW there was a gradual temperature increase of 1.4-2.3°C from a minimum at dawn to a maximum during mid-afternoon, on the ebb tide. There was slow overnight cooling (Fig. 2.2.2.1e).

Bottom currents (Fig. 2.2.2.1b) were continuous, averaging 0.17m s^{-1} and fluctuating without showing a clear relationship to the tidal cycle. Figure 2.2.2.1j shows the time:depth:current speed profiles with the separation of water masses indicated by the 32°/oo and 34°/oo isohalines. When unrestricted by the LSW, the current speed profile of the MIW shows a gradual increase from the substrate with maximum values between 1.0m and the water surface. To maintain the same volume transport when compressed by the LSW to a shallow, bottom layer, the bottom flow of MIW increased in speed two or threefold. This feature is shown repeatedly on the ebb tide. With the recession of the LSW lagoonwards of the platform, water transport was transferred to upper layers and bottom current speed immediately dropped (Figs. 2.2.2.1i and 2.2.2.ij). With the reefwards migration of the LSW during low water, an increase in bottom (MIW) currents was observed.

2.2.2.2. Schematic of backreef dynamics at the platform site Suva Reef.

The field observations suggest that the oceanography of the backreef zone may be considered as the equilibrium between four key variables:

1. Surfbeat: the combined effect of sea and swell conditions. Controls the volume of water (MIW) driven across the reef crest.

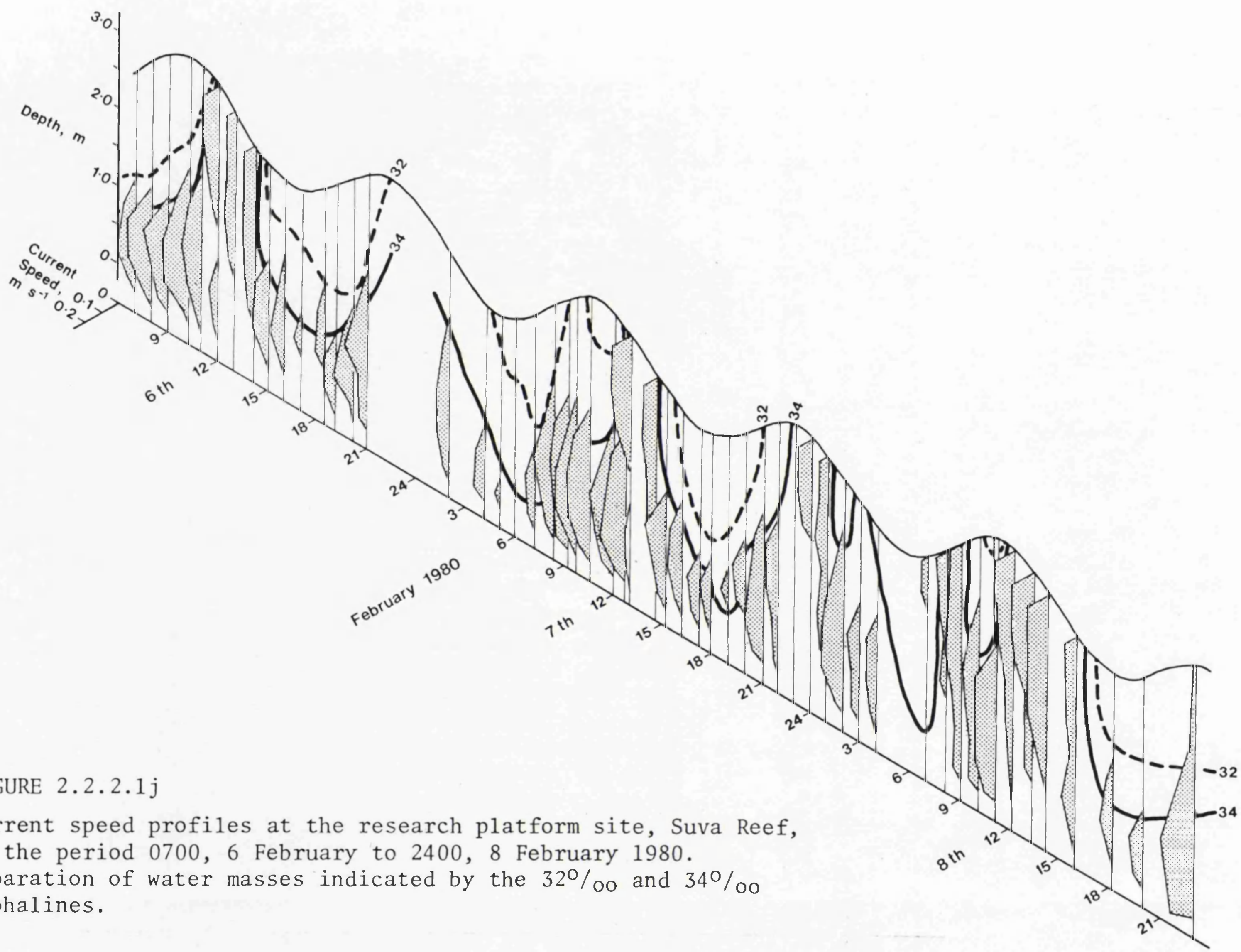


FIGURE 2.2.2.1j

Current speed profiles at the research platform site, Suva Reef, in the period 0700, 6 February to 2400, 8 February 1980. Separation of water masses indicated by the 32$^{o}/_{oo}$ and 34$^{o}/_{oo}$ isohalines.

2. River discharge: controls the salinity of the LSW and hence the stability of haloclines within the bay.

3. Wind speed and direction: affects (1) above, is responsible for shallow mixing of water masses in the bay and affects the circulation of LSW.

4. Tidal range: in conjunction with (1) above, controls reef emersion/immersion.

The resultant of this equilibrium is marked by the position of the convergence between the LSW and MIW. The perpetual migration of this front over the backreef area determines the conditions at the sea bed. The essential details of the dynamics of this area are shown schematically in Figure 2.2.2.2a.

LW+3: Wave-driven MIW floods across the reef top backed by the flooding tide. The convergent front is forced lagoonwards by this incursive water. Volume of flow depends on the surf characteristics. Current speed is proportional to the thickness of the MIW layer which, in the backreef, is related to the position of the LSW layer.

HW: MIW continues to be driven across the reef; the tide is slack. The position of the convergent front is variable, representing the equilibrium between wind speed and direction, river discharge (LSW characteristics) and volume of MIW flow.

HW+3: Tidal discharge from Laucala Bay; wave-driven currents persist across the reef top. Resultant outflow of LSW and MIW from the reef passages. With the release of pressure, the LSW ('ponded' in the bay on the flood tide) recedes and the convergent front moves lagoonwards.

LW: The tide is slack. If the reef top is emersed (spring tide, low

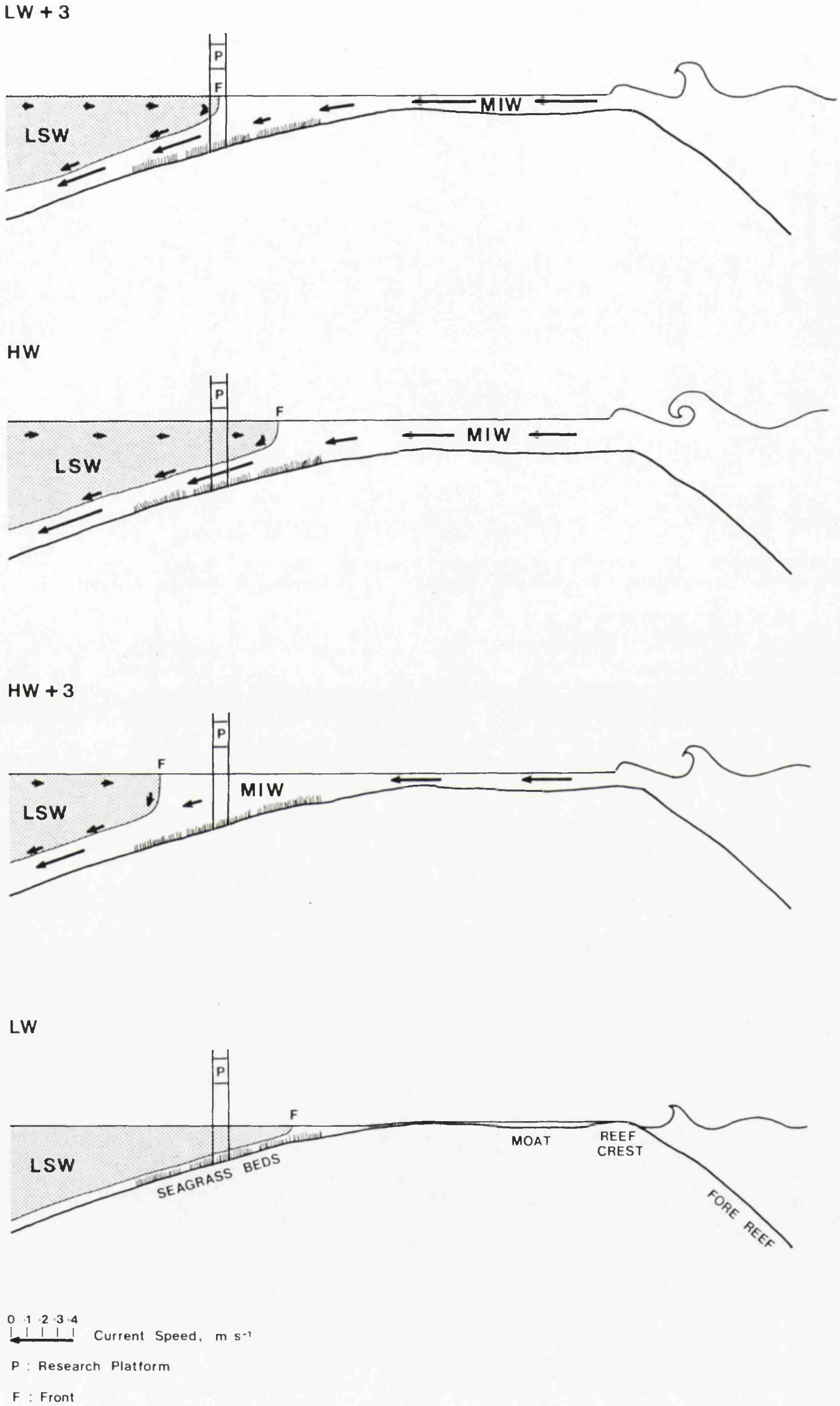


FIGURE 2.2.2.2a

Schematic of back reef hydrodynamics based on observations at the research platform site, Suva Reef.

wave conditions) residual waters drain into the lagoon. There is a reduction or complete cessation of backreef movement of the MIW. LSW meets no resistance and migrates reefwards. If the reeftop remains immersed (neap tides, extreme wave conditions) wave-driven incursive currents persist as HW+3.

Under extreme conditions of one or more of these four key variables, this schematic must be modified. With increased surfbeat the LSW:MIW front will be pushed lagoonwards and MIW flow will continue even on low water springs as the waves sweep over the reef crest. Calm offshore conditions lead to a reduction in suprareefal flow. Increased river discharge enhances the stability of the LSW:MIW halocline, acting as a barrier to vertical mixing. During flood events the hydraulic effect of the prism of water discharged over a tidal cycle becomes more prominent: it is estimated that a minor flood in the Rewa ($1000m^3\ s^{-1}$) will discharge freshwater equivalent to a layer 0.15m deep across Laucala Bay during one tidal cycle. During Cyclone *Wally* (3-5 April, 1980)(estimated return period of 70 years) peak flow was estimated at $9{,}000m^3\ s^{-1}$, sufficient to produce a freshwater layer 1.34m deep. Under such circumstances the MIW (marked by the front) will be pushed reefwards by the sheer 'weight' of freshwater. Since such catastrophic rains are frequently accompanied by high winds, the reefwards moving LSW is likely to be met by strong suprareefal currents driven lagoonwards by increased surf. Despite prolonged deployment of the continuous recording current meter, no observations were made under such extreme conditions. However, it is considered likely that such a combination of factors leads to generation of rapid, erosive, bottom currents. Further evidence for this is discussed in Chapter 4. Changes in wind direction can cause major changes in the backreef dynamics. Infrequent but often fresh SW winds have a dramatic effect on the bay: the LSW is ponded back towards the Rewa Delta (presumably to be released via the eastern distributaries) and the MIW extends throughout much of the bay. Strong SE winds tend to push the LSW shorewards, causing less increase in bottom current speeds than a strong NE wind which drives the LSW towards the reef, thereby compressing the MIW and accelerating the flow. Extreme low water is usually marked by reef emergence and a brief cessation of incursive flow. The timing of low water also determines the degree of exposure to insolation of ponded water. Favourable conditions can lead to brief pulses of high temperature water on the backreef slope, not necessarily associated with periods of maximum offshore water temperature. (Temperature of 32.5°C at the platform location during the last week in November, when the mean water temperature was 26.25°C. See Figure 2.2.1b.).

2.2.3. Namuka Reef: Proposed Dredge Site.

Observations were made from a floating raft anchored in 1.5m (below MSL, C.D. -0.6m) of water over the extensive seagrass beds which mark the proposed dredge site on Namuka Reef (Fig. 1.4.3a and Plate 1.1a). Measurements were made between 20 and 26 April 1980, with tides changing from springs to neaps (Fig. 2.2.3a). Winds were initially light and variable from the WNW - S sector. From April 23rd the area was subject to persistent ESE winds of 5-6m s^{-1} (Fig. 2.2.3a). Daily bright sunshine averaged 6.8hrs (Fig. 1.2.6a). Rainfall during April 1980 was exceptional: 924mm fell at Laucala Bay, 2.5 times the mean monthly value. The first period of excessive rain was associated with Cyclone *Wally* (Section 1.2.4. and Fig. 1.2.4b) from 3-5 April, the second came in the middle of the month, from 17-19 April. Both storms caused floods in the Rewa (Fig. 1.2.5b) with peak discharge of 9,000m s^{-1} and 1,600m s^{-1} respectively. In the three days prior to the first measurements, on April 20th, 120mm rain fell in the study area.

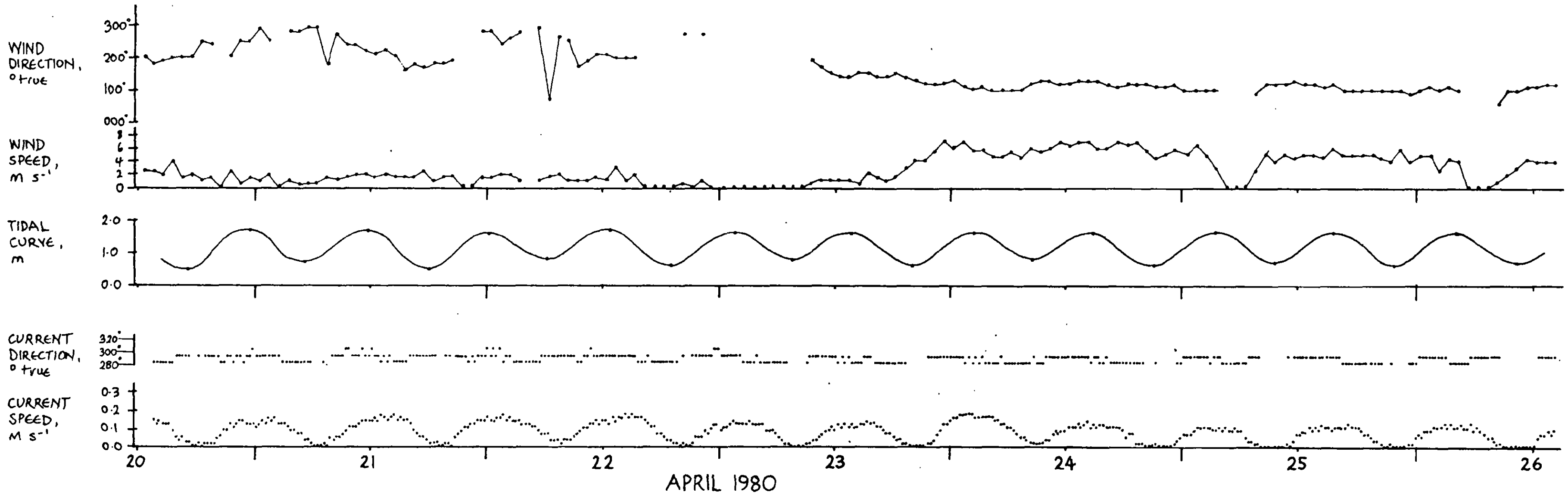


FIGURE 2.2.3a

Current meter record at the research raft site, Namuka Reef seagrass bed, in the period 20 to 26 April 1980. Wind speed and direction from FMS Laucala Bay Station. Tidal curve from Suva predictions (Admiralty Tide Tables, Vol. III, 1980).

The continuous bottom current record for the study site is shown in Figure 2.2.3a. The graph of current velocity mimics the tidal curve with displacement of the former approximately 1 hour along the time scale. There was a period of no movement or very slight flow for 1-2 hours commencing at low water (predicted). Velocity then increased gradually to a maximum of 0.10-0.18m s^{-1} sustained, at a uniform level in a WNW direction, for 4-6 hours over the high water period. Flow was reduced during the last three hours of the ebb and tended to veer 10-20° to the W, ceasing within 30 minutes either side of low water.

With few exceptions, the temperature and salinity profiles (Fig. 2.2.3b) were vertically homogenous. On April 20th there was a slight warming of the reef top waters, particularly during the 1800-1900 period when there was a cessation of water flow (Fig. 2.2.3a) at low water. There was an overall reduction in salinity of the suprareefal flow; values ranged from 32.29-33.21°/oo, a 5-8% admixture of freshwater. The following day, April 21st, salinity increased to 33.92-34.09°/oo, falling again on April 22nd to 32.99-33.84°/oo. Temperature fluctuations were slight, warming from 26.65°C on April 20th to a maximum of 27.55°C on April 22nd.

The second period of observations, 24-26April, were characterised by typical E-SE trade winds. The water column was invariably vertically homogenous, temperature ranging from 27.0 to 28.0°C, salinity from 31.15°/oo to 34.38°/oo, with no apparent pattern in the fluctuation of water characteristics.

Throughout the period of observations, the maximum salinity of the MIW was 34.35°/oo, considerably lower than the range considered typical of the MIW during the Suva Reef study; 34.7-35.0°/oo. The reduction in salinity is accounted for by the exceptional rainfalls during the three

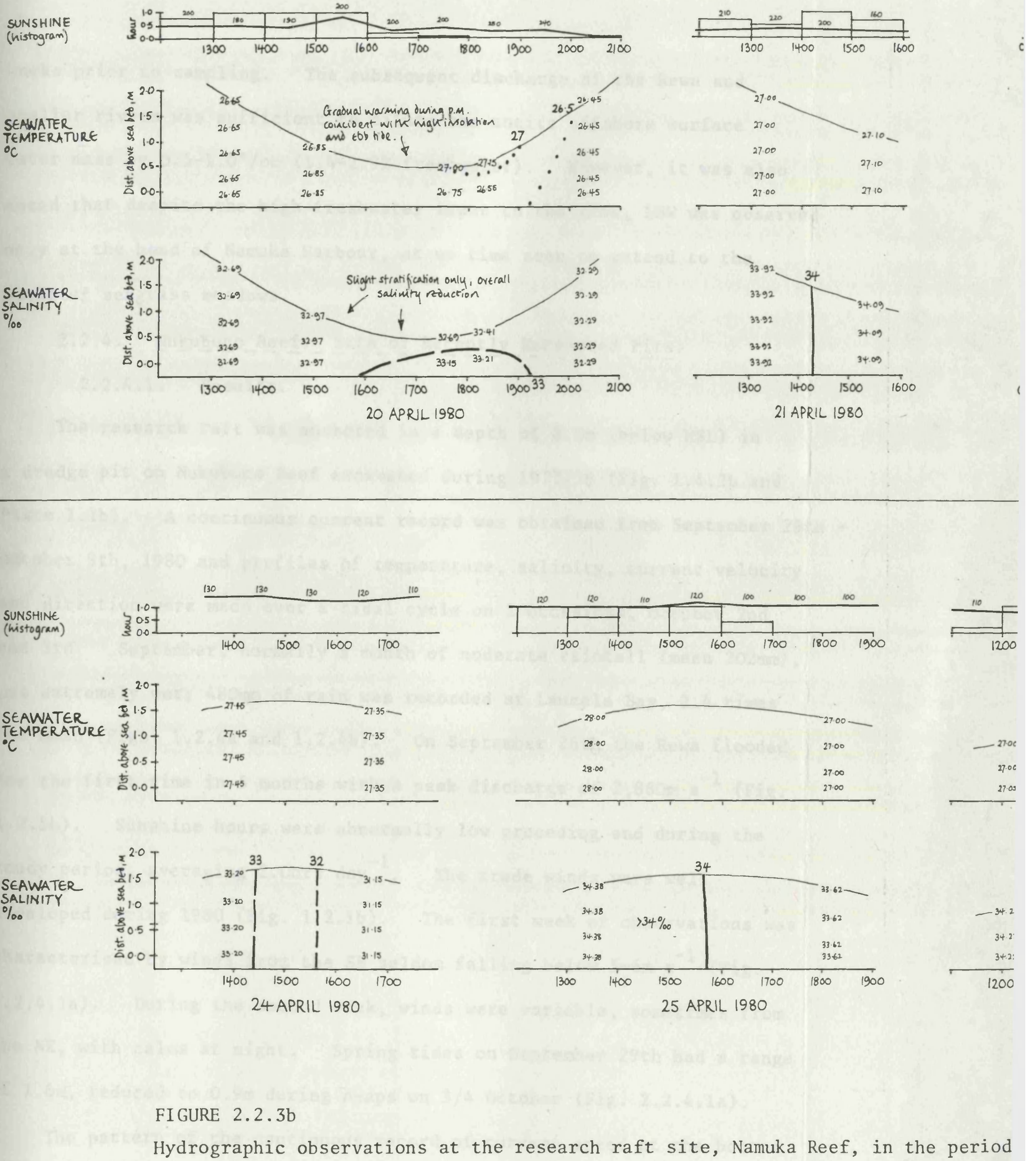


FIGURE 2.2.3b

Hydrographic observations at the research raft site, Namuka Reef, in the period weeks prior to sampling. The subsequent discharge of the Rewa and smaller rivers was sufficient to dilute the entire offshore surface water mass by 0.5-1.0°/oo (1.4-2.9% freshwater). However, it was also noted that despite the high freshwater input to the area, LSW was observed only at the head of Namuka Harbour, at no time seen to extend to the backreef seagrass meadows.

2.2.4. Nukubuco Reef: Site of Recently Excavated Pits.

2.2.4.1. Results.

The research raft was anchored in a depth of 8.5m (below MSL) in a dredge pit on Nukubuco Reef excavated during 1977/78 (Fig. 1.4.2b and Plate 1.1b). A continuous current record was obtained from September 29th - October 9th, 1980 and profiles of temperature, salinity, current velocity and direction were made over a tidal cycle on 2 occasions, October 2nd and 3rd. September, normally a month of moderate rainfall (mean 202mm), was extremely wet; 480mm of rain was recorded at Laucala Bay, 2.4 times the mean (Figs. 1.2.4a and 1.2.4b). On September 26th the Rewa flooded for the first time in 5 months with a peak discharge of 2,860m s^{-1} (Fig. 1.2.5b). Sunshine hours were abnormally low preceding and during the study period, averaging 2.0hrs day^{-1}. The trade winds were well developed during 1980 (Fig. 1.2.1b). The first week of observations was characterised by winds from the SE seldom falling below 5-6m s^{-1} (Fig. 2.2.4.1a). During the second week, winds were variable, sometimes from the NE, with calms at night. Spring tides on September 29th had a range of 1.6m, reduced to 0.9m during neaps on 3/4 October (Fig. 2.2.4.1a).

The pattern of the continuous record of current speed at the bottom of the dredge pit (Fig. 2.2.4.1a) shows a clear tidal relationship. On all except three ebbs (two 0.7m and one 0.5m tides, occurring during neaps) there was complete cessation of flow with each tidal cycle, occurring within

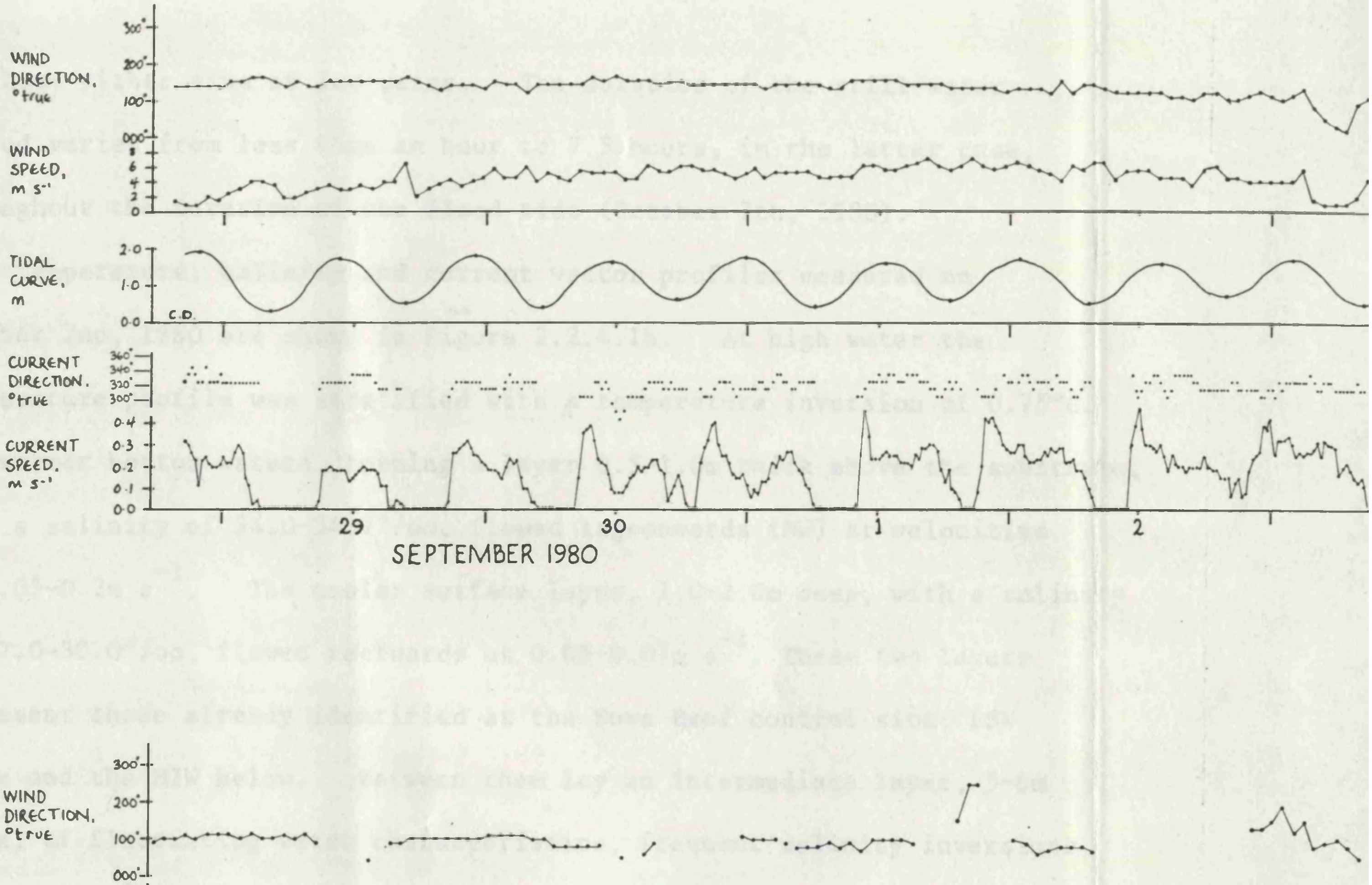


FIGURE 2.2.4.1a

Current meter record at the research raft site, Nukubuco dredge pit, in the period 29 September to 9 October 1980. Wind speed and direction from FMS Laucala Bay Station. Tidal curve from Suva predictions (Admiralty Tide Tables, Vol. III, 1980).

one hour either side of low water. The duration of the still-water period varied from less than an hour to 7.5 hours, in the latter case, throughout the duration of the flood tide (October 7th, 1980).

Temperature, salinity and current vector profiles measured on October 2nd, 1980 are shown in Figure 2.2.4.1b. At high water the temperature profile was stratified with a temperature inversion of 0.75°C. The warmer bottom waters, forming a layer 0.5-1.0m thick above the substrate, with a salinity of 34.0-34.7°/oo, flowed lagoonwards (NW) at velocities of 0.05-0.2m s^{-1}. The cooler surface layer, 1.0-2.0m deep, with a salinity of 27.0-30.0°/oo, flowed reefwards at 0.03-0.07m s^{-1}. These two layers represent those already identified at the Suva Reef control site; LSW above and the MIW below. Between them lay an intermediate layer, 5-6m thick, of fluctuating water characteristics, frequent salinity inversions and variable currents. As the tide ebbed, both the isotherms and isohalines diverged and were deflected sharply downwards. At low water the water column became isothermal and the tri-layer structure observed at high water was replaced by a graduated water mass with evenly spaced isohalines, from 27.6°/oo at the surface to 32.84°/oo at the sea bed.

The following day, October 3rd, observations were made between successive low waters (Fig. 2.2.4.1c). At low water the dredge pit was filled with a mixed water mass: surface LSW grading into an 'Intermediate' water mass. As soon as the tide flooded over the reef the isohalines were deflected upwards and the LSW was formed into a shallow surface layer. Total insolation for the day was only 0.5 hours and winds were continuous, 4-5m s^{-1}, from the ESE. The flooding MIW was marked by a minor bottom temperature increase of 1.05°C over 2 hours causing a vertical temperature inversion of 1.2°C. There was a strong lagoonwards (NW-NNW) flow, 0.2-0.3m s^{-1}, in the bottom layer, extending upwards into the turbulent

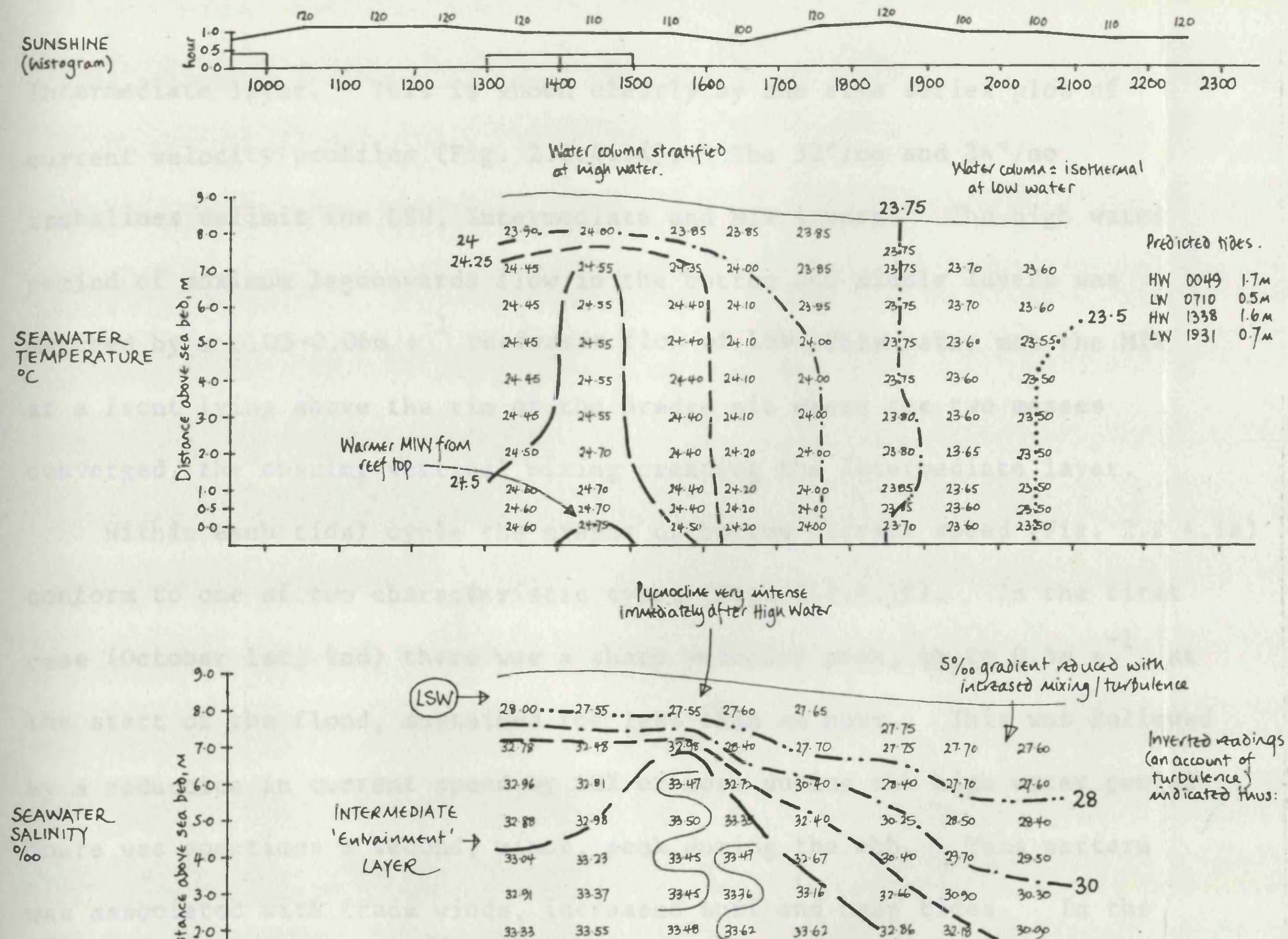


FIGURE 2.2.4.1b

Hydrographic observations at the research raft site, Nukubuco dredge pit, in the period 1300 to 2000, 2 October 1980.

Intermediate layer. This is shown clearly by the time series plot of current velocity profiles (Fig. 2.2.4.1d). The 32°/oo and 34°/oo isohalines delimit the LSW, Intermediate and MIW layers. The high water period of maximum lagoonwards flow in the bottom and middle layers was matched by a 0.03-0.06m s^{-1} reefwards flow of LSW. This water met the MIW at a front lying above the rim of the dredge pit where the two masses converged, the ensuing vertical mixing creating the Intermediate layer.

Within each tidal cycle the graphs of bottom current speed (Fig. 2.2.4.1a) conform to one of two characteristic types (Fig. 2.2.4.1f). In the first case (October 1st, 2nd) there was a sharp velocity peak, up to 0.5m s^{-1}, at the start of the flood, sustained for less than an hour. This was followed by a reduction in current speed by 50% or more during the high water period. There was sometimes a second, minor, peak during the ebb. This pattern was associated with trade winds, increased surf and neap tides. In the second type (October 6th, 7th), associated with variable E-NE winds, there was no flow during the flood tide; the bottom current started around high water and peaked during late ebb, attaining speeds of 0.3-0.4m s^{-1}.

The first peak marks the initial lagoonwards flood of MIW which is forced below the LSW in a thin, fast-flowing bottom layer that sweeps down the dredge pit slopes. Due to the steep, uneven substrate, turbulence rapidly develops within the pit and some flow is distributed into the Intermediate layer (Fig. 2.2.4.1d). This pattern, well developed in trade wind conditions, is completely absent in NE wind conditions (October 6th, 7th), when the LSW is pushed well across the reefflat, filling the dredge pit completely. During the ebb there is a release of water through the reef channels and a resultant withdrawal of LSW from the lagoon and reefflat. The MIW:LSW equilibrium is forced lagoonwards, the front lying along the rim of the dredge pits. MIW draining from the reef top flows under the

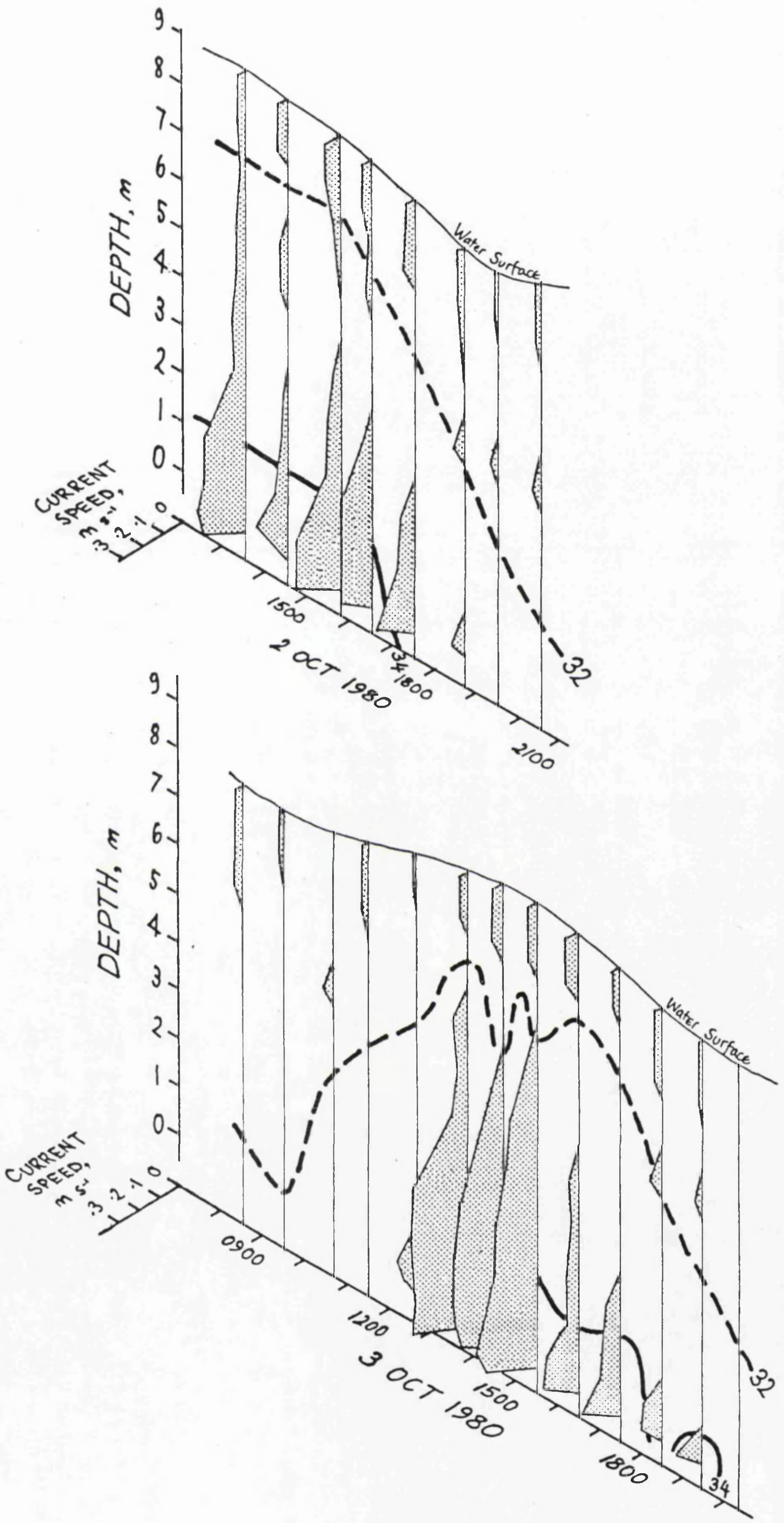
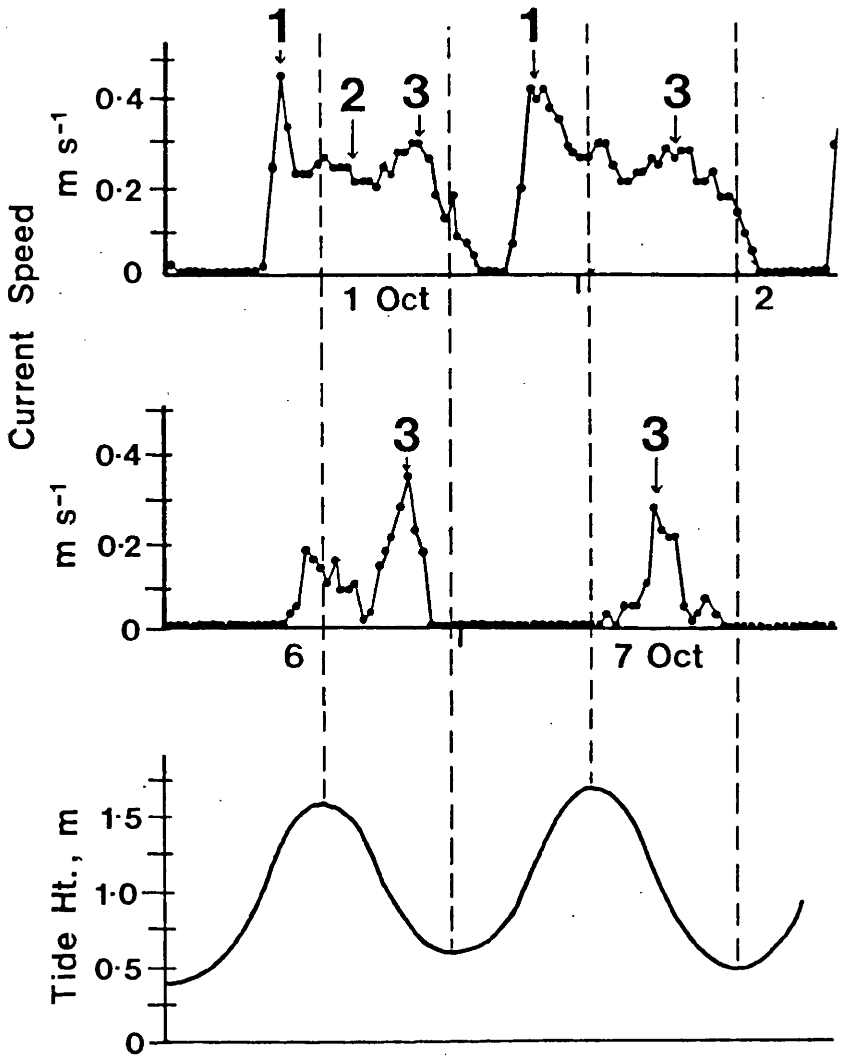


FIGURE 2.2.4.1d

Current speed profiles at the research raft site, Nukubuco dredge pit, in the periods 1300 to 2000, 2 October 1980 and 0800 to 2000 , 3 October 1980.
Separation of water masses indicated by the $32^o/_{oo}$ and $34^o/_{oo}$ isohalines.



PEAK 1 : wave-driven MIW, backed by prolonged SE winds and flood tide, is forced under LSW. Strong halocline restricts MIW to fast flowing bottom layer.

TROUGH 2 : turbulent Intermediate Water mass formed by mixing of LSW and MIW. Flow distributed through greater depth; bottom current speed reduced.

PEAK 3 : ebb tide; waters draining off the reef flat are channelled below the LSW/Intermediate Water.

FIGURE 2.2.4.1f

Detail of continuous bottom current speed record at Nukubuco dredge pit, 1 to 2 and 6 to 7 October 1980.

Extracted from Figure 2.2.4.1a

LSW producing current speed peaks seen on the ebb tide.

2.2.4.2. Schematic of dredge pit dynamics.

The physical oceanography of the dredge pits is a function of the same four key variables identified at the Suva Reef control site (surf-beat, river discharge, wind speed and direction, tidal range) modified by the unnatural topography created by the excavation of sand. A schematic of the dredge pit dynamics is shown in Figure 2.2.4.2.

LW: Slack water. If the reef top is emersed (spring tides, low wave conditions) there is no MIW flow. In the dredge pit a surface layer of LSW grades into a mixed Intermediate layer. If the reef top remains immersed (neap tides, extreme wave conditions) the Intermediate layer is underlain by a thin bottom layer of MIW.

LW+3: MIW floods over reef and is forced below the lower salinity water mass in the dredge pit. The hydraulic pressure of the LSW and Intermediate layers, confined to the bay by the tide flooding through the reef passages, compresses the MIW layer. Maximum bottom current velocities.

LW+5: Entrainment of LSW by the MIW creates Intermediate water; some lagoonwards transport is distributed to the Intermediate layer. LSW, replenished from the lagoon, flows reefwards in a shallow layer separated by a halocline from the Intermediate water.

HW: Tide is slack. Waters in the dredge pit are increasingly turbulent and mixed. LSW flow continues towards the convergence where it is entrained into the lower layers.

HW+3: There is a release of pressure on the LSW, maximum at mid-tide. Incursive flow is distributed through the MIW and Intermediate, turbulent, layer.

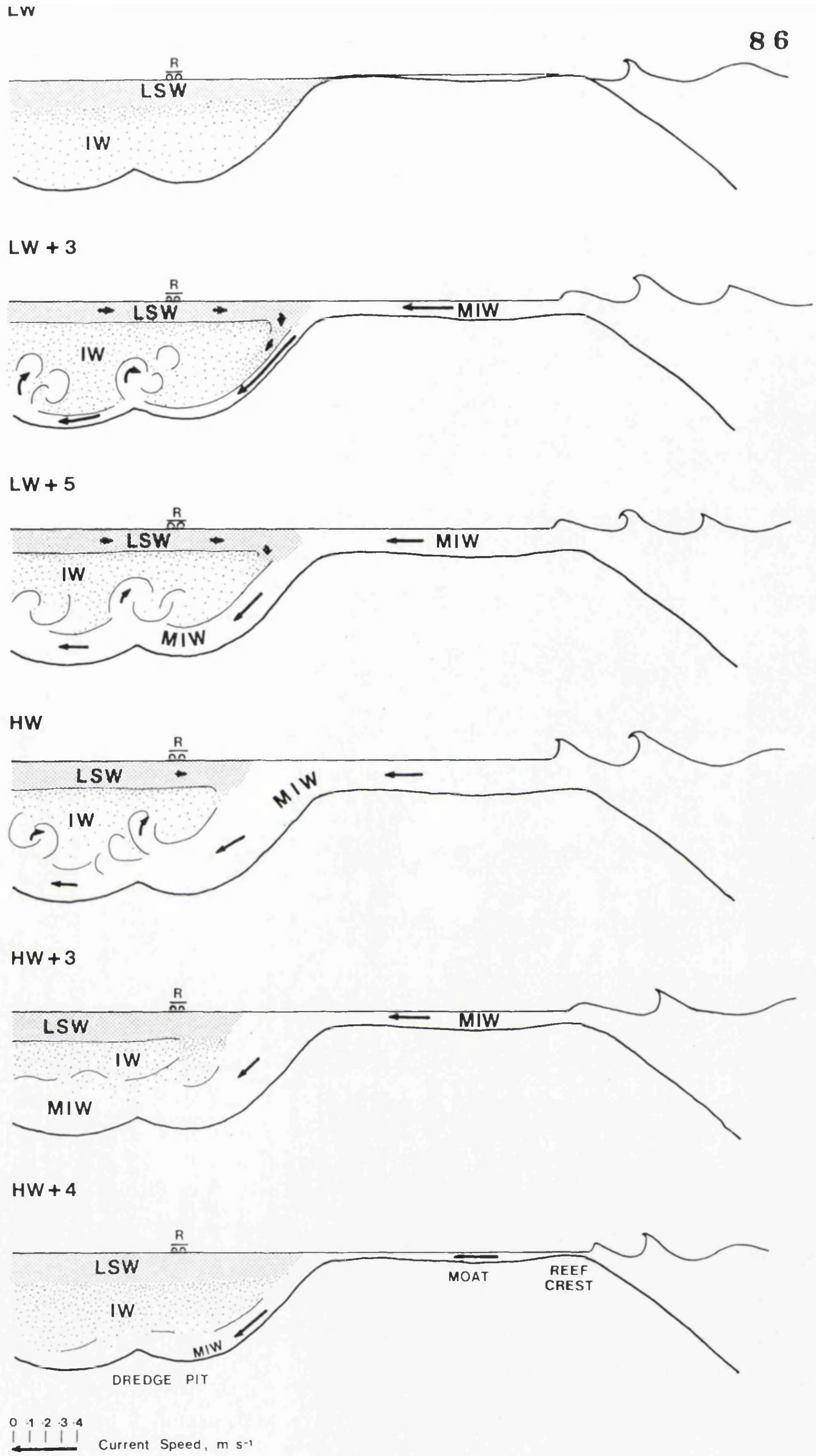


FIGURE 2.2.4.2

Schematic of dredge pit hydrodynamics based on observations at the research raft, Nukubuco dredge pit.

HW+4: As the ebb progresses there is drainage of residual waters from the reef; continued wave-driven input on neap tides. As low water nears, the pressure release of LSW through the channels is reduced. The front moves reefwards towards the dredge pit rim particularly when backed by E-NE winds. MIW flow is confined and bottom lagoonwards velocities may reach a second peak.

2.2.5. Reef Emersion.

The continuous recording current meter was deployed in three locations for a total of 98 tidal cycles (see Figs. 2.2.2.1b, 2.2.3a, and 2.2.4.1a). An analysis was made to determine the relationship between predicted height of low water and cessation of flow ($\leq$ 0.01m s^{-1}) over the same low water period (Table 2.2.5a).

When the incursive current drops below 0.01m s^{-1} it is assumed that the reef crest is completely emersed. The effects of emersion are several. Exposed sedentary organisms on raised areas of the reef crest and reef flat may be subject to desiccation and cooling by the wind or desiccation and heating by the sun. They are also deprived of the water flow, often precluding feeding and interrupting photosynthesis and respiration. Under conditions of high insolation, organisms remaining immersed in enclosed pools may be subject to gradual water temperature increase of 10°C or more (Ryland et al., 1983). On the flood tide, cooler oceanic water floods across the reef top causing a very rapid reduction in temperature. The effect of the warmed waters, forced lagoonwards by the incoming tide, extends beyond the tidal reef top into the subtidal lagoon slopes (this study). Brief pulses of warmed water, 3.5°C above ambient (Fig. 2.2.2.1e) were observed over the seagrass meadows of Suva Reef and there is evidence that, during the cooler months, much greater fluctuations take place

TABLE 2.2.5a. ANALYSIS OF CONTINUOUS CURRENT METER RECORDS. FREQUENCY OF OBSERVATIONS WHEN SUPRAREEFAL CURRENT CEASED, OR CONTINUED, FOR 0.1m INTERVALS OF PREDICTED LOW WATER. EXPRESSED AS PERCENTAGES AND PLOTTED IN FIGURE 2.2.5a.

Predicted Low Water (m)	Suva Reef: Platform				Nukubuco Reef: Dredgepit				Namuka Reef: Study Site			
	Ceases		Continues		Ceases		Continues		Ceases		Continues	
	obs.	%	obs.	%	obs.	%	obs.	%	obs.	%	obs.	%
0.1												
0.2	1	100										
0.3	3	100			1	100						
0.4	5	71	2	29	2	100						
0.5	10	71	4	29	9	90	1	10	2	100		
0.6	9	43	12	57	5	100	0	0	4	100		
0.7	3	16	16	84		0	2	100	3	100		
0.8			1	100					2	66	1	33
0.9												
TOTALS:	31		35		17		3		11		1	

(Predicted low water heights from Admiralty Tide Tables, Vol. III, 1979 and 1980).

(Section 2.1.1. and Fig. 2.2.1b)(cf. mean annual offshore seawater temperature range of 5°C, Section 1.3.2.1.).

Whether or not emersion occurs is a function of tidal height and wave conditions. Consider the observed tide to match precisely the predicted tide and the sea to be flat calm; then emersion would occur at, or below, a clear-cut predicted low tide level. The observed tide may vary from the predicted but seldom more than 0.05m (see Fig. 2.2.2.1c). The observed spread of values (Table 2.2.5a. and Fig. 2.2.5a) is, therefore, mainly due to variation in sea and swell conditions. On Suva Reef the flow ceased on tides falling to only 0.7m yet continued on tides falling as low as 0.4m. With no synoptic quantitative wave data, it is assumed that flow ceased on a 0.7m tide only during conditions of flat calm whilst it continued, during conditions of heavy surf, on several 0.4m tides. Indeed this was visually observed on many occasions.

The 50th percentile, H_{50}, gives the predicted tidal height for which there is a 50% chance that the reef will be emersed and that flow will cease. The value of H_{50} differs between reefs, lowest on Suva Reef, 0.55m (66 obs.)and highest on Namuka Reef, 0.85m (12 obs.). Nukubuco Reef has an intermediate value, 0.63m (20 obs.).

These reef emersion data are meaningful only if combined with the annual low water predictions (time and height) shown in Figure 1.3.1a. It has been established that it is the occurrence of daytime ebbs that are potentially most stressful to the reef community. The frequency of daytime ebbs (0600-1800) for each 0.1m level was counted for the periods June to August, 1979 and December 1979 - February 1980 (Admiralty Tide Tables, Vol. III)(Fig. 2.2.5b). These frequencies were then multiplied by the percentage of occasions (observed) when reef emersion occurred for each 0.1m level on each reef (Table 2.2.5b).

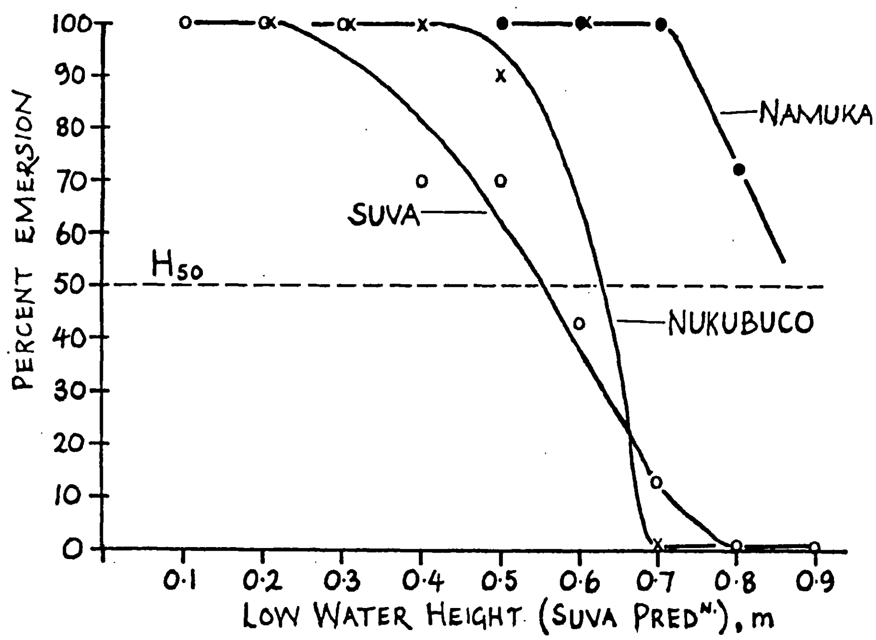


FIGURE 2.2.5a

Percentage of observations of reef emersion versus predicted low water height (Admiralty Tide Tables, Vol. III, 1980).

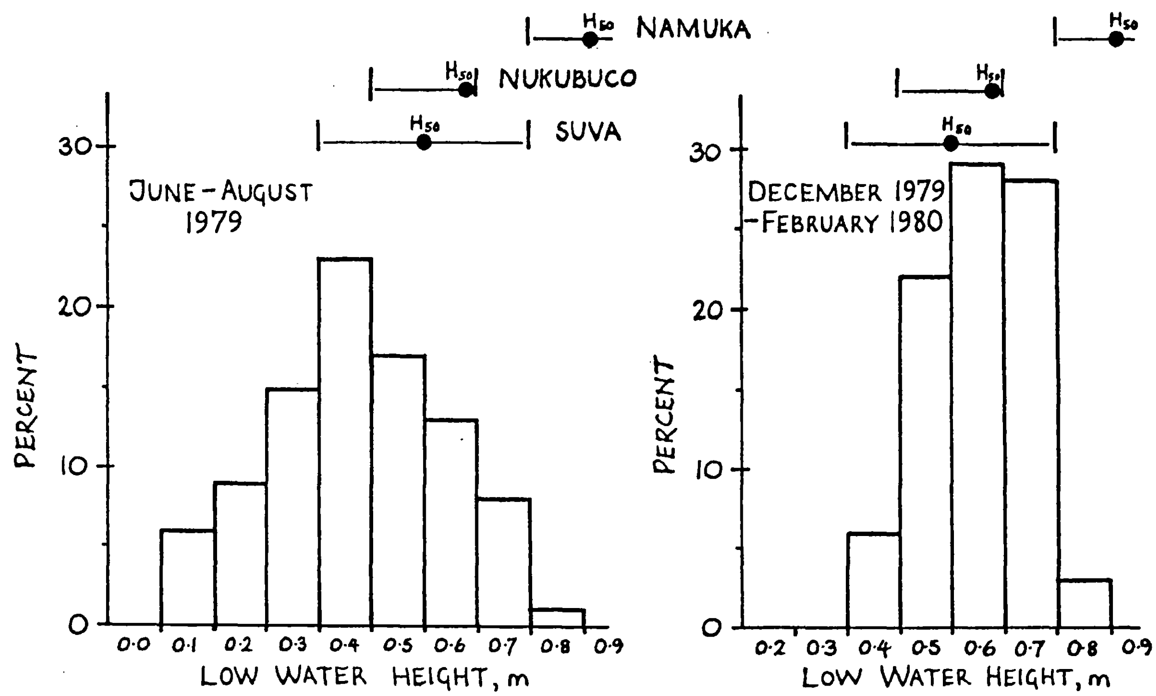


FIGURE 2.2.5b

Frequency (percent) of daytime (0600-1800) ebbs in the periods June to August 1979 (winter) and December 1979 to February 1980 (summer). Suva predictions (Admiralty Tide Tables, Vol. III, 1979, 1980). Emersion/Immersion ranges and H_{50} indicated for Suva, Nukubuco and Namuka Reefs.

TABLE 2.2.5b. PREDICTED NUMBER OF OCCASIONS (PE) WHEN THE REEF WILL BE EMERSED AT LOW WATER BETWEEN 0600 AND 1800 (I.E., DAYLIGHT HOURS) FOR SUVA, NUKUBUCO AND NAMUKA REEFS. TIME PERIODS: JUNE-AUG.1979; DEC. 1979-FEB. 1980.

Predicted Low Water (m)	Suva Reef			Nukubuco Reef			Namuka Reef		
	E %	P	PE	E %	P	PE	E %	P	PE
June, July, August, 1979.									
0.1	(100)	6	6	(100)	6	6	(100)	6	6
0.2	100	9	9	(100)	9	9	(100)	9	9
0.3	100	15	15	100	15	15	(100)	15	15
0.4	71	23	16	100	23	23	(100)	23	23
0.5	71	17	12	90	17	15	100	17	17
0.6	43	13	6	100	13	13	100	13	13
0.7	16	4	1	0	4	0	100	4	4
0.8	0	1	0	(0)	1	0	66	1	1
Total		88	65		88	81		88	88
December 1979, January, February, 1980.									
0.1	(100)			(100)			(100)		
0.2	100			(100)			(100)		
0.3	100			100			(100)		
0.4	71	6	4	100	6	6	(100)	6	6
0.5	71	22	16	90	22	20	100	22	22
0.6	43	29	12	100	29	29	100	29	29
0.7	16	28	4	0	28	0	100	28	28
0.8	0	3	0	(0)	3	0	66	3	2
Total		88	36		88	55		88	87

E: percentage of observations at each 0.1m tide level when incursive current ceased ($\leqq 0.01\text{m s}^{-1}$) during low water period. From Table 2.2.5a.

P: frequency of predicted daytime (0600-1800h) ebbs for each 0.1m tide level during the three month period (Admiralty Tide Tables, Vol. III, 1979, 1980).

Between June and August 1979 (winter) it is estimated that from a total of 88 daytime ebbs, Suva Reef was emersed for 65 (74%), of which 30 were lower than 0.35m, the lower limit of the 'emersion/immersion' range (i.e., the range of low water levels at which, on separate occasions, both emersion and immersion were observed). This compares with the December 1979 to February 1980 period (summer) when of a total 88 daytime ebbs it is estimated that the reef was emersed only 36 times (41%). During this interval the lowest predicted ebb was only 0.4m and therefore it is to be expected that the duration of each emersion was also considerably less.

No account is made in these calculations for possible variations in H_{50} and the emersion/immersion range occasioned by seasonal changes in the wave climate or mean sea level.

Values are also given for Nukubuco and Namuka Reefs. For the latter it is estimated that ~~during the winter months emersion would occur on 3 of 88 ebbs and during the summer, not at all.~~ reef emersion would occur during the winter months on every daytime ebb and during the summer months on 87 out of 88 daytime ebbs. Data for this reef is very limited and collected at one season only. However, the fact that emersion occurred on all but one of the observed ebbs (92%; cf. 40% of ebbs of comparative levels on Suva Reef) is strong evidence that there is a real difference between the levels of Suva and Namuka Reefs. For Nukubuco Reef also, data are limited and the incidence of reef immersion appears to contain an anomalous zero frequency at the 0.6m level.

2.2.6. Laucala Bay: Water Exchange and Tidal Currents.

Water flow over the reef is unidirectional; incursive. Ideally, calculation of suprareefal water input into Laucala Bay required synoptic observation of MIW (Marine Incursive Water) depth and velocity over the reef top. In practice, data were collected in the backreef area (from the research platform) where the MIW was intermittently confined to a shallow, fast-flowing, bottom layer, of variable thickness. Transport in a restricted MIW layer 1.0m thick with a velocity of 0.4m s^{-1} (1800, 2 February, 1980, Fig. 2.2.2.1g) was similar to that of an unconfined layer 2.5m deep with a velocity of 0.16m s^{-1} (1100, 2 February, 1980). For the purpose of this simple mathematical model, two transport rates (T) were considered:

Rate	Depth, m	Velocity, m s^{-1}	Transport (T), m^2 s^{-1}
High	2.0	0.15	0.3
Low	2.0	0.05	0.1

It was assumed that this rate of transport was maintained for an average duration, D; 0.75 of each tidal cycle (12.4h x 0.75 x 3600 = 3.348×10^4s). The length of reef (L) over which there is incursive flow (assumed to be uniform along the entire length) is approximately 6×10^3m (Nukubuco Reef, 3.5×10^3m; Suva Reef, 2.5×10^3m).

Then the input of water (I) over the reeftop during one tidal cycle can be expressed:

$I = L \times T \times D$ m^3 tidal cycle^{-1}

For the high transport rate, I = $6.03 \times 10^7 m^3$ tidal cycle^{-1}. Distributed over Laucala Bay, area $4.5 \times 10^7 m^2$, this represents a layer of water 1.34m deep during one complete tidal cycle or a layer 0.67m deep during one flood tide.

For the low transport rate, I = $2.01 \times 10^7 m^3$ tidal cycle^{-1}, a prism of water 0.45m deep, 0.22m deep during one half cycle.

Mean tidal range is 1.3m on springs, 0.9m on neaps (Table 1.3.1). It is possible then that during periods of high flow, particularly on neap tides (longer duration of flow and reduced range), the majority of the tidal prism may enter Laucala Bay via suprareefal flow.

Were the entire tidal prism to enter by either suprareefal flow, river discharge or a combination of both, then there would be no input through the reef passages. This situation is most likely to occur during extreme conditions, particularly following a cyclone. After Cyclone *Wally* the Rewa discharge was gauged to peak at 9000m³ s^{-1} (Section 1.2.5), estimated to contribute to Laucala Bay, during one flood tide, a freshwater prism 0.67m deep (1.34m during the complete tidal cycle). Combined with a suprareefal incursive flow of similar proportions (high transport rate, backed by storm waves impinging on the reef) these inputs could account for a tidal elevation exceeding the mean spring tidal range.

Measurement of current velocity and direction in the reef channels, particularly Nukubuco Passage, was a problem unresolved in this study. The passages are all prohibited anchorages (on account of submarine cables), also narrow routes frequented by interisland trading vessels. Being in excess of 50m deep and exposed to the open ocean sea conditions, the use of SCUBA to moor current meters was also precluded.

In contrast to the previous supposition (that a combination of suprareefal flow and freshwater inputs may, on occasion, exceed the tidal prism), there were occasions during the study of Nukubuco dredged area when no MIW flow was recorded during the flood tide (Fig. 2.2.4.1f). Unfortunately no synoptic data are available to confirm whether or not this also occurred on Suva Reef. However, assuming that it did, then the entire tidal prism must have entered through the reef passages. Three passages connect Laucala Bay with the open ocean:

Passage	Estimated Cross-sectional Area,* m²
Laucala Is. to Nukulau Is.	6030
Nukulau	5025
Nukubuco	10050
Total	21105

*From British Admiralty Chart 1757.

A spring tidal incursion of 1.3m over Laucala Bay, area $4.5 \times 10^7 m^2$, would require a tidal prism (P) of $5.85 \times 10^7 m^3$. It is estimated that this prism would enter through a cross-sectional area (CS) of $2.1 \times 10^4 m^2$ during one flood tide (T), 6.2h. Then the mean incursive current velocity on a spring tide (Vspring) is calculated as:

$$Vspring = \frac{P}{CS \times T \times 3600} \ m\ s^{-1}$$

$$Vspring = 0.12m\ s^{-1}.$$

It is unlikely either that the flow would be distributed uniformly over the cross-section of the passage, or that the rate of flow would be constant throughout the tidal cycle. From the tidal curve (Admiralty Tide Tables, Vol. III) it is evident that 50% of the elevation of the tide occurs during the two midtide hours. Incursive current velocities (over the entire cross-section) of $0.19m\ s^{-1}$ would be required to satisfy these conditions.

During a neap tidal incursion of 0.9m, $P = 4.05 \times 10^7 m^3$, $Vneap = 0.09\ m\ s^{-1}$ and Vneap (during the midtide period) = $0.13m\ s^{-1}$.

On the ebb tide, the tidal prism of $4.05 - 5.85 \times 10^7 m^3$ must be emptied through the passages, along with the suprareefal and freshwater inputs which may be maintained throughout this period. Transport through the passages will invariably be outgoing on the ebb tide. It is suggested that, in places, current velocities will be greater, under extreme conditions as much as twice the maximum incursive velocities. No quantitative data are available to verify this.

2.3. Discussion.

The LSW is primarily a feature of Laucala Bay, extending, on account of the connection of the two basins, into Suva Harbour. In these areas this water mass is present in all but exceptional circumstances and overlies a layer of marine waters. The latter are a mixture of waters entering the lagoon over the reef top and through the passages. The suprareefal incursion of marine waters is a feature common to the whole area: the volume of flow being proportional to the exposure of each particular area to the prevailing swell.

In Laucala Bay the hydrography of the backreef zone is regulated by the equilibrium between the MIW and LSW. At the control site, the interaction of these water masses may result in an increase by two or three times in the bottom current velocities. In the dredge pits, due to the increased resistance offered by the deep layer of LSW/Intermediate Water ponded there, this effect is exacerbated. The consequent intensification of bottom currents leads to decreased deposition and increased erosion of sediments (Chapter 4). After dredging, the rapid currents also reduce the possibility of settlement of seagrass seeds or fragments of vegetative material leading to recolonization (Chapters 3 and 5).

The increase in the sediment load of the Rewa River has significantly raised turbidity levels in the LSW under both prevailing and catastrophic conditions. Below the LSW there has been an insidious reduction in the intensity, and change in the composition, of the light, to the probable detriment of plant growth on the sea bed (Section 3.2.2.). In the control area, this turbid LSW layer undergoes erratic cycles of recession from the backreef, allowing periodical illumination of the seabed through the clearer MIW. Within the dredge pits the LSW forms a screen of both increased depth and opacity which seldom recedes lagoonwards, reducing still further the potential for regrowth of seagrass.

West of Suva Harbour the effect of the LSW is greatly diminished, haloclines are less stable and there is less interference of illumination due to turbidity. The greater clarity of waters in the Waiqanaki dredge pits is evidenced by the natural occurrence of seagrasses in Waiqanaki II and III.

Lami Reef, location of Waiqanaki I and II, is sheltered from the prevailing SE swells by Suva Reef. The volume of MIW flow is reduced and being less constrained by LSW it flows freely into Suva Harbour and Rattail Passage. Waiqanaki III, although close nearby on Namuka Reef, is subject to a quite different hydrographic environment. Shorewards of the central section of Namuka Reef (Waiqanaki to Muaivuso) there is no lagoon connected to the open ocean. MIW flows across the reef and to escape is then deflected along the shore, SW to Namuka Harbour, NE to Rattail Passage. Much of the latter component of this flow is funnelled into the dredge pit Waiqanaki III from where it then exits to the passage (Plate 1.1a). Although no measurements were made in this area, current velocities on the ebb tide, particularly during conditions of high wave energy, were invariably strong, estimated 0.3m s^{-1}.

The proposed site for future dredging on Namuka Reef (Plate 1.1a) resembles Waiqanaki III in that it is largely unaffected by LSW but differs in that there is release for the MIW across the wide reef flat into Namuka Harbour. Consequently it is expected that after dredging, this area would not be prone either to the current intensification caused by LSW:MIW interaction, or, to any great extent, to the funnelling of currents.

3. Biology

CHAPTER 3. BIOLOGY.

3.1. Introduction.

Prior to excavation, 50-55% of the now dredged area was covered by dense seagrass meadows (Section 1.4.2.). The remainder consisted of unvegetated sand and rubble with a sparse infauna and epifauna. Following excavation, the sea bed was lowered to a depth of 7-10m below C.D. resulting in displacement of all the free-living fauna and complete destruction of the seagrass beds.

Assessment of the impact of these excavations requires an understanding of the role and contribution of the seagrass prior to excavation, both to the remaining meadows and to the reef ecosystem as a whole.

The magnitude of the task of studying a seagrass ecosystem was discussed by den Hartog (1979). He proposed that such a study should focus on five essential aspects: structure, function, dynamics, history and classification.

3.2. Seagrass Community: Structure.

Structure comprises several overlapping components; the floral and faunal elements of the community, their spatial distribution, temporal fluctuations, interrelationships and relations with the surrounding environment.

Den Hartog (1979) listed nineteen structural elements of the seagrass community; headed by the seagrass leaves, roots+rhizomes and including their epibiota, the free-swimming fauna and planktonic biota, the companion macro- and micro-algae, and the sessile and vagile macro, meio and micro epi- and infauna. The collection and identification of these organisms and analysis of their role within the community was a task beyond the scope of this study. Furthermore to pick on any one particularly visible group of organisms in isolation might be to infer some undue emphasis on their importance to the community (the "dazzle effect"). Within the seagrass community it is the seagrasses that form the bulk of the biomass. The seagrass leaves, roots and rhizomes also form the frame of the community on which most of the other elements depend. In Fiji, the indispensability of the seagrass as the basic structural element of the community is evidenced by the impoverished biota of the neighbouring unvegetated sand areas. Thus, within the scope of this study, greatest emphasis was placed on the structural and functional analysis of the framework element; the seagrass. However, this work was not initiated simply as an academic study of various aspects of a seagrass ecosystem; rather, it aimed to relate to the day-to-day activities of the indigenous people who exploit the impacted reef areas, particularly for subsistence and artisinal fisheries for turtle, fish, beche-de-mer and sea urchins. For this reason, observations on the structure and function of the community also included the exploitable elements listed above.

3.2.1. Seagrass Species Occurring in SE Viti Levu.

At the outset of this study, four species of seagrass had been recorded from SE Viti Levu: *Syringodium isoetifolium* (Aschers.) Dandy, *Halodule pinifolia* (Miki) den Hartog, *Halophila ovalis* (R. Br.) Hook. and *Halophila minor* (Zoll.) den Hartog; (den Hartog, 1970; Parham, 1972; Smith, 1979). McMillan and Bridges (1982) made a detailed examination of *Halophila* from the Suva region. They concluded that the consistently small-leaved plants, with either smooth or bullate leaves, should be separated from *H. ovalis* and treated either as an endemic taxon or placed with other small-leaved populations of the Pacific in *H. minor*, as a polymorphic taxon. Extensive subtidal collections during 1979-1982 (this study) verified the presence of an additional species; *Halodule uninervis*

(Forssk.) Aschers.

3.2.1.1. *Syringodium isoetifolium* (Aschers.) Dandy.

S. isoetifolium is the most abundant seagrass in Fiji. In Laucala Bay it forms two zones, one on the terrigenous mud flats adjacent to the shore, the other on the carbonate sand deposits found at the inner margin of the reef. Along the edge of the mud flats, *S. isoetifolium* forms a narrow band, 5-10m wide, immediately below LWS. On the backreef slopes the meadows are more extensive, generally ranging in width from 50-200m (Section 1.4.2. and Fig. 1.4.2a). The average depth range is 0.5-4.0m below C.D. but exceptionally, in dredge pit Waiqanaki III, a substantial area (ca. $10m^2$) of naturally revegetated *S. isoetifolium* was observed at 8.0m below C.D. (17th October, 1980). However, when this area was revisited 17 months later (February, 1982) there was no trace of this seagrass.

A feature of all the backreef seagrass meadows is the random pattern of bare sand areas interspersed between patches of dense growth. The reticulation is irregular and shows no favoured orientation (cf. the sand waves and "blowouts" described by Patriquin (1975) and found intertidally on Makuluva Reef). A similar pattern in areas of *S. isoetifolium* in the Seychelles was attributed to the activities of burrowing crustaceans (Taylor and Lewis, 1970). Although crustacean mounds are to be found in the backreef seagrass meadows in Fiji, they constitute only a small fraction of the reticulated bare sand areas. Maintenance of the equilibrium between seagrass and bare sand is probably by a combination of biological and oceanographical controls.

Figure 3.2.1.1a shows the depth profile of the transect line on Suva Reef. Using a $1m^2$ quadrat divided into $1/16m^2$ sections, percentage seagrass cover was determined in a band 1m wide by 150m long (the length

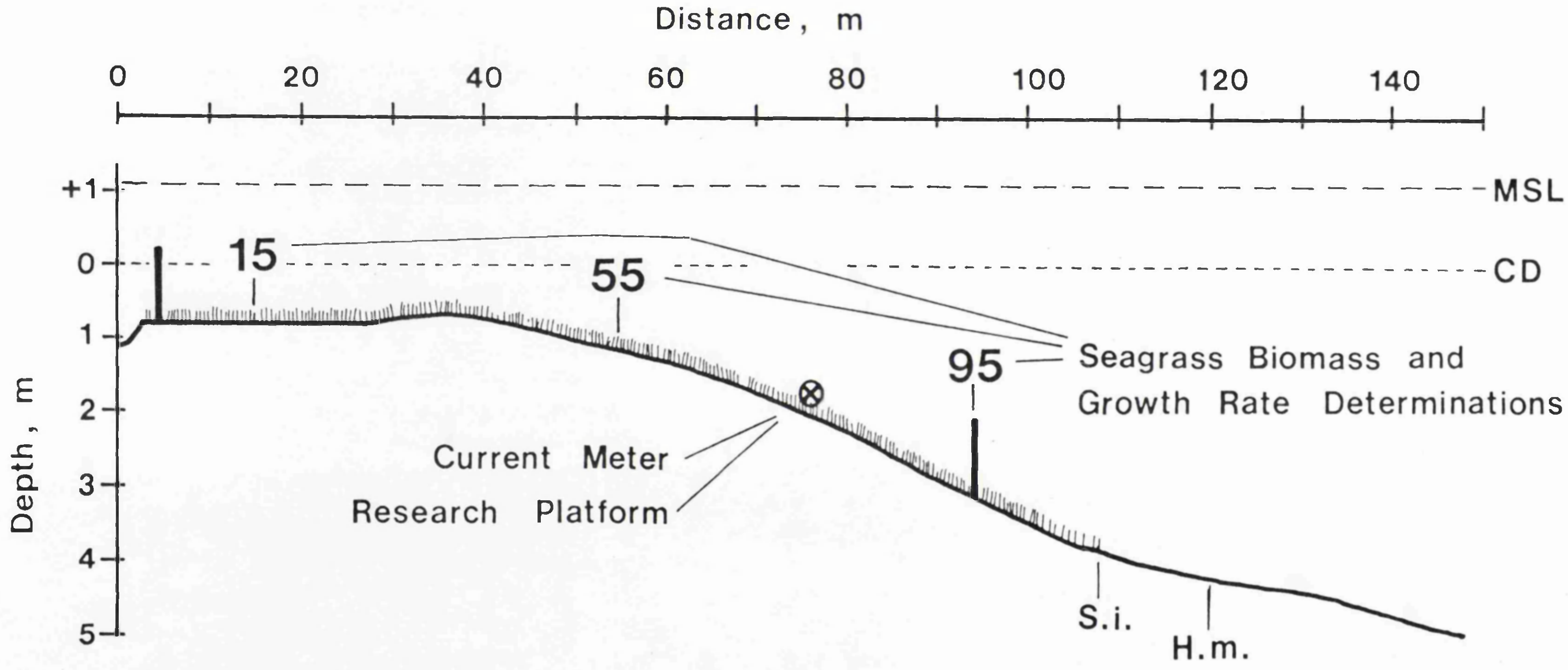


FIGURE 3.2.1.1a

Depth profile of the Suva Reef transect line, location of the research platform (for location, see Figure 2.1a).

S.i. : limit of depth penetration of *Syringodium isoetifolium*
H.m. : limit of depth penetration of *Halophila minor*

of the transect). Percentage cover for individual quadrats ranged from 0-100%. Mean values for ten combined quadrats (averaged between successive stakes) ranged from 32-82% (Table 3.2.1.1a). Mean seagrass cover over the whole vegetated length of the transect line was determined twice. A value of 62% was obtained on October 30th, 1980, 55% on 19th March, 1982. The difference is not significant ($P > 0.05$).

The occurrence of flowering of *S. isoetifolium* was regularly monitored at three locations (Table 3.2.1.1b). Flowering was first observed on 18th October, 1979 on Nukubuco Reef. During October, November and December flowers were found in meadows on Nukubuco, Suva and Waiqanaki Reefs. At all these locations the inflorescences were very sparsely distributed amongst the vegetative material and diligent searching was necessary. All the flowers were found in subtidal meadows. The *S. isoetifolium* flowers collected at Draveuni, Great Astrolabe Reef (Fig. 1.1a), were found in a meadow offshore from the village at 2m below C.D. where the inflorescences made up 50-70% of the above ground biomass. Following the observation of 8th February, 1980 on Suva Reef, no further flowering material was found during the succeeding 6 months. On 25th August, 1980 flowers were observed in the intertidal beds on Makuluva Reef and the subtidal beds on Nukubuco Reef. During September and October flowers were found on Waiqanaki and Suva Reefs.

S. isoetifolium is dioecious, that is, male and female flowers are carried on separate inflorescences (den Hartog, 1970). The entire collection of *S. isoetifolium* inflorescences, made periodically during 1979-1980, numbered many hundreds. Without exception, every single flower was pistillate (female). Not one staminate (male) flower was found. Furthermore, neither seeds, nor signs of seed formation were observed.

TABLE 3.2.1.1a. PERCENTAGE COVER OF *SYRINGODIUM ISOETIFOLIUM* ON SUVA REEF TRANSECT LINE.

Position Along Transect Line Stake Numbers*	% Cover by *S. isoetifolium*	
	30 Oct 80	19 Mar 82
1 - 2	68	58
2 - 3	73	57
3 - 4	70	53
4 - 5	72	44
5 - 6	45	37
6 - 7	74	69
7 - 8	68	65
8 - 9	80	82
9 - 10	40	56
10 - 11	32	33
Mean	62	55

*For positions of stakes see Fig. 3.2.1.1a.

All stakes were 10m apart.

Percentage cover averaged over 10m intervals.

TABLE 3.2.1.1b. OBSERVATIONS OF PISTILLATE FLOWERS OF *SYRINGODIUM ISOETIFOLIUM*, FIJI, 1979-1980.

Month	Makuluva	Nukubuco	Suva	Waiqanaki	USP	Draveuni
1979 Oct	X	18,29	20,21,27	.	X	31
Nov	.	7	5,7	.	.	.
Dec	X	2,30	3,10,24,31	9	.	.
Jan	.	.	.	.	.	.
Feb	X	.	8	.	.	.
Mar	X	X	X	.	X	.
Apr	X	X	X	.	X	.
1980 May	X	X	.	.	.	.
June	X	X	X	.	.	.
July	.	.	.	.	.	.
Aug	25	25	.	.	.	.
Sept	.	.	.	8	.	.
Oct	X	X	16	17	.	.

X - search carried out, no flowers observed.

16,23 - search carried out, date(s) of observation of flowers.

. - no search made.

Site	Depth
Makuluva	C.D. + 0.2m; exposed at LWS.
Nukubuco	C.D. - 0.5m
Suva	C.D. - 2.2m
Waiqanaki	C.D. - 0.5m
USP	C.D. + 0.2m; exposed at LWS.
Draveuni	C.D. - 2.0m.

The only anomalous structures, found on 3rd December, 1979, were a stage in the breakdown of female flowers that did not get fertilized (C. McMillan, pers. comm.).

3.2.1.2. *Halophila minor* (Zoll.) den Hartog.

Halophila minor is the most eurybiontic seagrass species in Fiji. It is found on substrates ranging from fine terrestrial muds (e.g., USP breakwater, Suva Harbour) to coarse coral rubble (e.g., Nukubuco, Suva and Namuka Reefs). During this study it was found to extend from C.D. + 0.8m (Suva Point) to C.D. -17.0m (Namuka Passage). In some areas it is completely exposed on the ebb tide and close to the Rewa discharge it is periodically subjected to low salinity ($\geq 1°/oo$) waters.

On the mudflats adjacent to the shore *H. minor* occurs in copious mats in the lower intertidal zone (C.D. to C.D. +0.8m), frequently associated with *Halodule pinifolia*.

H. minor is a pioneer species. In Fiji it is generally the first species to colonize a suitable area of recently disturbed sand by establishment either of a fragment of vegetative material or of a seedling. *H. minor* produces viable seeds in abundance. The seeds germinate viviparously (within the fruit). The seedlings, with one leaf pair, are readily distributed by wave and current action. Flowering and seed production was widespread during October-December, 1979 (Table 3.2.1.2a). No observations were made in January, 1980 but between February and May no further flowers or fruits were found. A solitary male flower was found at Makuluva on 10th June, 1980. No further data were collected until mid-August. Flowering was then observed at all the sites examined during August-October, 1980.

H. minor has a poor competitor status. In the backreef region it has a bifid distribution, cleft by the *S. isoetifolium* meadow. Where

TABLE 3.2.1.2a. OBSERVATIONS OF FLOWERS, FRUITS AND SEEDS OF *HALOPHILA MINOR*, FIJI, 1979-1980.

Month	Makuluva	Nukubuco	Suva	Waiqanaki	USP
1979 Oct	M,F,FR,S	F,FR	M	X	X
Nov	M,F,FR,S	F,FR	F	.	X
Dec	M,F,FR,S	M,F,FR	X	M	.
Jan	.	.	.	.	.
Feb	X	.	.	.	.
Mar	X	X	.	.	.
Apr	.	X	.	.	.
May	X	X	.	.	X
1980 Jun	M	.	.	.	X
Jul	.	.	.	.	.
Aug	M	M	.	.	M,F,FR,S
Sep	.	.	.	M,F	.
Oct	.	.	M,F,FR,S	.	.

M = Staminate (male) flower

F = Pistillate (female) flower

FR Ripe fruit

S = Germinating seeds (seeds are viviparous, i.e., germinate within the fruit).

X = Search carried out: no sexual reproductive structures found.

. = No search made.

Site	Depth
Makuluva	C.D. + 0.2m, exposed at LWS.
Nukubuco	C.D. - 0.5m.
Suva	C.D. - 2.2m.
Waiqanaki	C.D. - 0.5m.
USP	C.D. + 0.2m, exposed at LWS.

its range extends higher than the *S. isoetifolium* it colonizes emergent sandbars (usually in association with *Halodule pinifolia*) and sand areas between coral heads/microatolls in the moat. Below the lower limit for *S. isoetifolium* growth it colonizes the deeper lagoon slopes. Within the *S. isoetifolium* zone it is occasionally found on the bare sand areas interspersed through the meadow.

3.2.1.3. *Halodule pinifolia* (Miki) den Hartog.

Halodule pinifolia is widespread in Fiji but is of little bearing on the sand dredging operations.

On the shoreward mudflats *H. pinifolia* is found both in pure stands and in association with *Halophila minor*, extending from C.D. +0.8m to C.D. -2.0m. *H. pinifolia*, like *Halphila minor*, is a pioneer species and unable to compete successfully in regions where *Syringodium isoetifolium* thrives. On the backreef its distribution is limited to sand deposits that are regularly exposed at low water, thus precluding growth of *S. isoetifolium*.

H. pinifolia flowers and fruits in Fiji. On 9th September, 1979, flowering material was observed at Pacific Harbour (S coast of Viti Levu) on a black sand beach. Subsequently flowers and fruits were observed on Makuluva Reef (November 7th, 1979) and Nukubuco Reef (October, 27th, 1980).

3.2.1.4. *Halodule uninervis* (Forssk.) Aschers.

Prior to this study, *Halodule uninervis* had been found with certainty in Fiji, only in the lagoon of Fulaga Is. (Fig. 1.1a)(Smith, 1979).

In Laucala Bay, *H. uninervis* may be found at ELWS at the bottom of the USP boat slipway. Here it forms extensive beds rooted in fine mud 100-200mm deep, overlying a soapstone basement. A smooth-leaved form of

Halophila minor is sparsely distributed through these beds. During 1979-1980 this was the only location at which *H. uninervis* was found in S.E. Viti Levu.

H. uninervis was also found at Lakeba Is. (Fig. 1.1a) during July 1979 (in seagrass meadow directly in line with the jetty at Tubou Harbour on the seaward side of the boat channel). This was the sole location where, during this study, the four seagrass species were observed in a mixed stand. *S. isoetifolium*, *Halophila minor*, *Halodule pinifolia* and *H. uninervis* were all collected at C.D. -2.0m on fine coral sand.

During 1982 *H. uninervis* was recorded at the transect line on Suva Reef. It was found in a mixed stand with *S. isoetifolium* at stake 10, C.D. -3.2m (see Fig. 3.2.1.1a).

Flowering material of *H. uninervis* was not found during this study.

3.2.2. Factors Affecting the Growth and Distribution of Seagrass.

The growth and local distribution of seagrass is affected by many interrelated factors. Amongst the most important are light, temperature, salinity, nutrients, pressure, wave movement, substrate and competitors. Colonization of a new area or recolonization of a disturbed area depends on the same group of factors applied serially to a succession of species. It is also dependent on a supply of seed or vegetative material.

Unravelling the interrelationship between seagrass and environment, particularly determination of the prime, or limiting, factors affecting growth, demands two different types of information. Data are required to describe the physiological response of each seagrass species to each environmental parameter (or, better, combinations of parameters), for example; photosynthetic inhibition, saturation and compensation irradiances, upper and lower salinity and temperature tolerances, minimum nutrient levels, pressure tolerance, requirement/tolerance of wave and/or current action, substrate requirements and tolerance of competition (overgrowth by epibiota, grazing, etc.)(e.g., den Hartog, 1970; McMillan, 1976; Burrell and Schubel, 1977; McRoy and McMillan, 1977; Drew, 1978, 1979; McMillan, 1980, 1982; Beer and Waisel, 1982). The second type of data required are a complete description of the meteorological and hydrographical environment (to which the seagrass responds). Such data must include observations of both prevailing and episodic conditions: it is possible that it is the duration and range of the perturbations, not the means, which are of importance (i.e., limiting).

However, faced with constraints on time, equipment and expertise, there are two key issues; firstly, the rate (and seasonality) of growth, secondly, the depth limit for growth (both of which reflect the interactions of a number of environmental variables).

One of the prime factors affecting growth, identified in numerous recent studies, is light. The amount of light reaching the sea bed, the irradiance, is a function of solar radiation, cloud cover, light reflectance of the water surface and light transmittance through the water column. Sand-Jensen (1975) found that maximum leaf production of *Zostera marina* coincided with maximum solar radiation. Aioi et al. (1981) obtained similar results. They considered that photosynthetic activity is unlikely to be light saturated and would therefore depend upon total daily solar radiation. However, Clough and Attiwill (1980), showed that for *Zostera muelleri* (Westernport Bay, Australia), photosynthesis was light saturated for the greater part of each day and the seasonal variation in net primary production was therefore strongly influenced by day length. Williams and McRoy (1982) proposed that seagrass productivity increases proportionately to light until a saturation irradiance is reached where light is no longer limiting and productivity reaches a maximum value. At this level other environmental conditions can become controlling factors. This was evidenced by Drew (1979) who found that light-saturated photosynthetic rates increased in direct proportion to temperature increase (over the normal temperature range experienced in the habitat). He estimated that light saturation occurred at ca. 10% full sunlight. Kirkman et al. (1982) found that growth of *Zostera capricorni* is more closely related to water temperature than solar radiation (or solar radiation lagged by one month). Demonstrating further the complexity of the issue, Drew (1978) found that maximum photosynthetic rates were not correlated with maximum production. He found that gross photosynthesis in *Posidonia oceanica* was directly related to the chlorophyll content of the leaves. During the summer, despite increased irradiance and water temperature he observed a *reduction* in gross photosynthesis by comparison to the spring. He attributed this to a decline in leaf chlorophyll content, probably due to leaf senescence (rather than to shading).

Light is also identified as a key factor in restricting the lower depth limit of seagrass distribution. Seagrasses are clearly zoned in the sublittoral, some ranging to C.D. -2m others to C.D. -60m (den Hartog, 1977). Compensation irradiances must vary between species. Drew (1979) estimated the compensation irradiance for several seagrasses to be ca. 1% of full sunlight, while Buesa (1974) proposed a limit of ca. 25% of surface irradiance for *Thalassia testudinum*. From distributional data for marine and freshwater angiosperms Bulthuis (1983) estimated a minimum irradiance requirement of 5-15% of surface irradiance. Backman and Barilotti (1976) and Mukai et al. (1980) found that the depth distribution and abundance of *Zostera marina* was correlated with the level of irradiance. Maximum irradiance does not necessarily correlate with maximum insolation on account of variation in the turbidity of the water. Buesa (1974)

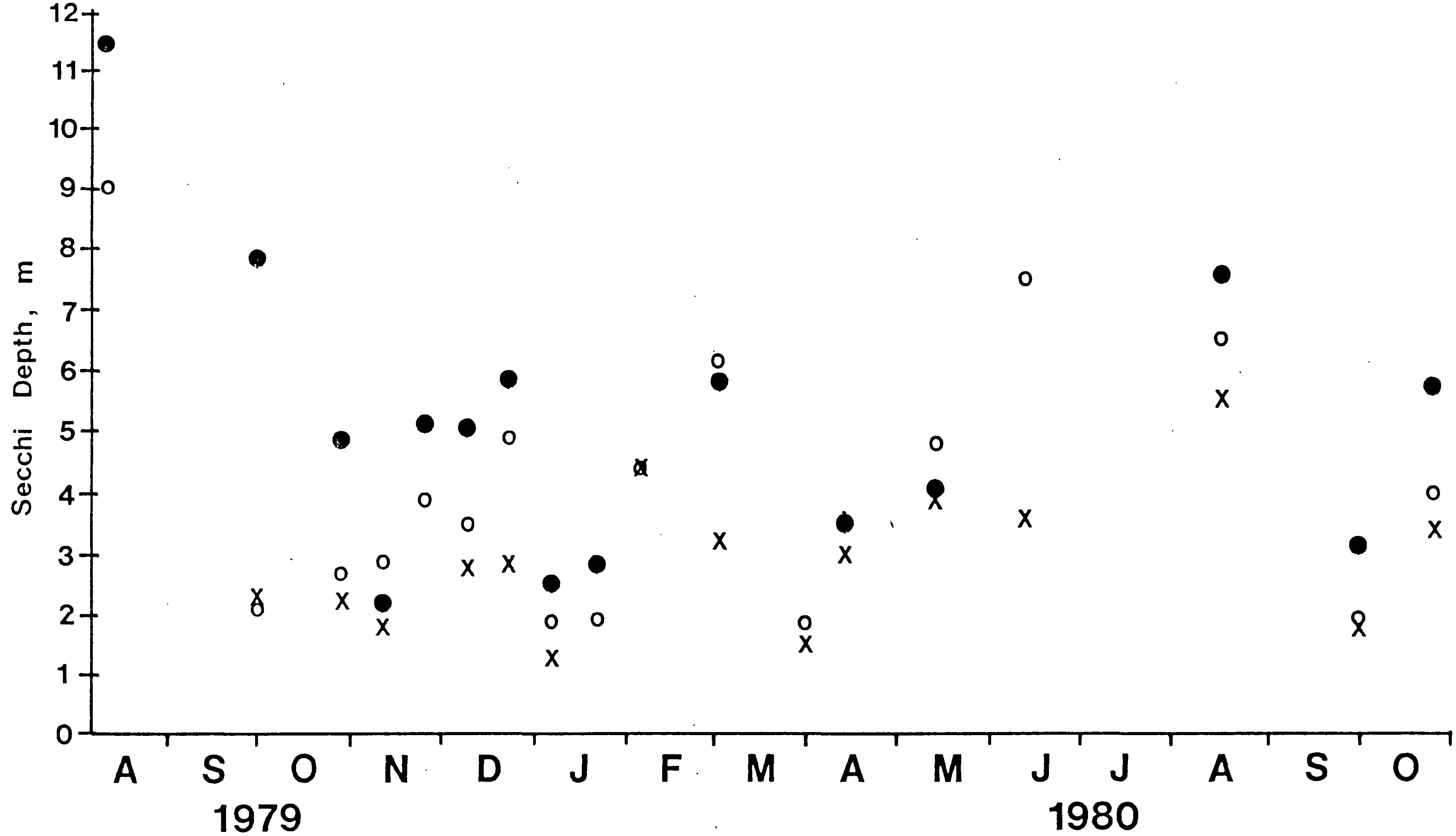


FIGURE 3.2.2.1a

Secchi depths measured at Laucala Bay oceanographic stations (Figure 2.1a) in the period September 1979 to October 1980.

X Laucala Bay Station 1

o Laucala Bay Station 2

● Laucala Bay Station 3

and Bulthuis (1983) both point to light as the major factor controlling depth penetration of seagrasses. However, there are other depth variable factors, including pressure. The effect of pressure was investigated by Beer and Waisel (1982) who found that although *Halodule uninervis* was not light limited to a depth of 15m, it is never found deeper than 5m (Red Sea); the limit to the depth penetration of this species was attributed to pressure.

This study is primarily concerned with one seagrass species, *Syringodium isoetifolium*. There are no data concerning the physiological response of this species to light, temperature or pressure. Several authors briefly record the depth range of this species: sublittoral belt, exceptionally to C.D. -6m (den Hartog, 1970); C.D. -1m to C.D. -5m (Lipkin, 1977); just below LWN (Young and Kirkman, 1975).

3.2.2.1. Measurement of irradiance.

Records of daily sunshine hours for the period of the study were available from Laucala Bay Meteorological Station (Fig. 1.2.6a). Additional information included daily variation in the zenith angle of the sun, day-length and the reflectance of the sea for given sun angles (Fig. 1.2.6b, insets). However, no combination of these data can be used to estimate sea bed irradiance. The one unknown factor is the transparency/turbidity of the water, known to be highly variable over the seagrass meadows. The periodic transgression and regression of the turbid lagoonal surface water layer over the backreef slope was described in Chapter 2.

Vertical secchi depths were taken at the three oceanographic stations in Laucala Bay (Fig. 3.2.2.1a; see Fig. 2.1a for locations). These give an indication of the range of water transparency throughout the year. Maximum clarity was observed during the winter months, particularly during conditions of southwest winds. Minimum clarity was observed during the summer months, especially after periods of high rainfall over the land.

No pattern of turbidity variations could be quantified from secchi depths in the backreef seagrass zone, since the disc was frequently visible on the sea bed. Horizontal secchi distances were of doubtful use for estimation of sea bed irradiance. Some quantitative value of surface irradiance plus measurement of the depth of each water layer (MIW clarity was frequently 3 times greater than the LSW) was still required.

A true record of sea bed irradiance can only be obtained by *in situ* measurement. To be meaningful in terms of the seagrass meadows, design of such measurement should account for:

(i) the activity spectrum of the photosynthetic pigments in the seagrass (and its epiphytes). The spectrum of the irradiance through the MIW is quite different from that below the LSW.

(ii) the duration and intensity of light. Irradiance at a level higher than the light saturation intensity of the plant is not utilized.

Measurements of this quality were not possible during this study.

3.2.3. Elements of the Seagrass Community Exploited by Indigenous Peoples.

The seagrass meadows already or potentially affected by sand dredging are also readily accessible to the local population of Suva and the nearby villages. These villagers have relatively sophisticated technology at their disposal: e.g., punts with outboard engines and monofilament gillnets. They are encouraged to fish both at a subsistence and at an artisinal level (i.e., to catch for export or sale in local markets). It was not feasible to make a survey of the pattern of fisheries throughout the study area. In this study a qualitative faunal survey was carried out in one area. It was restricted mainly to those species exploited by fisherpersons.

3.2.3.1. Vertebrates.

Fish were collected from the seagrass meadows by spearing, hook and line, and trawling with a 1.5m x 0.7m aperture beam trawl. Thirty-one species of fish were recorded (Table 3.2.3.1a). Many evaded capture, particularly the smaller species, such as pipefishes and seahorses, some of the nocturnal visitors, flutemouths and squirrelfish, and other miscellaneous groups, garfish and eels. The fish can be broadly classified into 3 categories (Hoese, 1978); resident, temporary resident and nursery species. The resident group comprises mainly small-sized species such as gobies, blennies, pipefish, triggerfish and some wrasse. Temporary residents are generally more mobile and enter the seagrass beds to feed or breed. Included in this group are the emperors, mullets, larger wrasse and parrotfish. Many of these fish seek shelter from predators in the coral patches and bombies of the reef moat and lagoon slopes. Nursery species spend the early stages of their life cycle in the beds before moving to other reef areas as they mature. The main nursery species are the barracuda, rabbitfish and some of the mullets and wrasse.

For the Fijians fishing in the seagrass meadows the main food fish are the emperors; kabatia, sabutu and sabutuloa. These are caught on prawn-baited lines working from a punt or standing in the water. Other species, some of the wrasse and juvenile barracuda, are also taken in this way. Gillnets are used, worked between a pair of punts, capturing a much wider variety of fish. Except for a few known toxic species, nearly all the fish are eaten, regardless of size. Of the nursery species, the rabbitfish, *Siganus canaliculatus* and *S. vermiculatus* are probably the most important food fish (Woodland, 1979). These are caught, as adults, elsewhere on the reef; lagoon bombies, reef passages and forereef.

In addition to the fish, the green turtle, *Chelonia mydas* is also

TABLE 3.2.3.1a. FISH SPECIES RECORDED IN SEAGRASS MEADOWS ON SUVA REEF.

FAMILY, common name Scientific name	fijian name	food fish
SYNODONTIDAE, lizardfish		
Synodus englemani	utimate	N
Synodus variegatus	utimate	N
BOTHIDAE, left-handed flounder		
Bothus pantherinus	dadavilai	E
SPHYRAENIDAE, barracuda		
Sphyraena sp.	oqo	E*
APOGONIDAE, cardinalfish		
Apogon exostigma	tina	E
LUTJANIDAE, snapper		
S.f. NEMIPTERINAE, monocle-bream		
Scolopsis cancellatus	kabatia	E
S.f. LETHRININAE, emperor		
Lethrinus ? harak	kabatia	E
Lethrinus ? mahsena	sabutu	E
Lethrinus ? rubrioperculatus	sabutuloa	E
MULLIDAE, red mullet, goatfish		
Mulloidichthys vanicolensis	ki	E
Parupeneus barberinoides	ose	E
Parupeneus barberinus	mataroko	E
POMACENTRIDAE, damselfish		
Amblyglyphidodon curacao	?	?
LABRIDAE, wrasse		
Cheilinus bimaculatus	labe	E
Novaculichthys macrolepidotus	?	?
Chelio inermis	saresareninuku	E
Thalassoma trimaculatus	? labe	?
Halichoeres trimaculatus	labe	E
SCARIDAE, parrotfish		
Calotomus spinidens	ulavi	E
Scarus sp.	ulavi	E

FAMILY, common name Scientific name	fijian name	food fish
PARAPERCIDAE, grubfish		
Parapercis cylindrica	utimate	N
Parapercis cephalopunctatus	?	?
SIGANIDAE, rabbitfish		
Siganus canaliculatus	nuqa	E
Siganus ? vermiculatus	rusarusa	E
GOBIIDAE, goby		
Amblygobius phalaena	?	?
Amblygobius sphynx	?	?
SCORPAENIDAE, scorpion fish		
Scorpaena sp.	lewamatua	E
ECHENEIDAE, remora		
Echeneis naucrates	bakewa	E
BALISTIDAE, triggerfish		
Sufflamen chrysopterus	cumu	E
Rhinecanthus aculeatus	cumu	E
TETRAODONTIDAE, pufferfish		
Arothron hispidus		

Fish caught by spearing, hook and line and trawling. Fijian names and edibility of the fish also recorded.

E = edible

N = Not edible

? = Not known.

E* Some species of barracuda may be toxic at certain times of the year.

Authorities for generic and specific names: Appendix IV.

caught in the seagrass meadows, where it feeds. There is heavy pressure on the turtle population in Fiji as a whole, in Laucala Bay in particular (M.L. Guinea, pers. comm.). They are caught in nets set at the entrances to the reef passages and by spearing from outboard-powered punts.

3.2.3.2. Invertebrates.

Several invertebrate species are exploited at a subsistence or artisinal level.

Beche-de-mer (holothurians) were once an important export from Fiji (ca. 1900). There have been periodic attempts to revive interest in this industry (Gentle, 1979; Conand, 1981). It is particularly attractive on account of the low investment required. At least 9 species were found in the seagrass meadows (Table 3.2.3.2a). From the backreef meadows, only one species, *Microthele fuscogilva*, is actually collected and processed on a regular basis. However, except for the work of Conand (1981), very little is known of the biology of this species, particularly recruitment and growth rate. The fishery in Fiji apparently is completely opportunistic. *Metriatyla* sp. is more commonly found on muddy shores from where it is collected and sold locally.

The sea urchin *Tripneustes gratilla* (fij.: cawaki) was found abundantly in the seagrass meadows, usually well camouflaged by seagrass leaves. On breaking the test the gut was invariably packed with fragments of *S. isoetifolium* leaf-blades (cf. Phillips, 1980a). These urchins are collected and sold in the market.

Two molluscs are collected from the seagrass meadows at a subsistence level: the spider conch *Lambis lambis* (fij.: yaqa) and the sea hare *Aplysia* sp. (fij.: veata).

TABLE 3.2.3.2a. MAIN HOLOTHURIAN SPECIES FOUND IN SEAGRASS MEADOWS IN LAUCALA BAY.

Scientific Name	Fijian name	Potential Use
Microthele fuscogilva	sucuwalu	o.m.*
Microthele nobilis	loaloa	o.m.
Actinopyga crassa	dri	o.m.
Actinopyga echinites	dri tabua	o.m.
Metriatyla sp.	dairo	l.m.*
Stichopus chloronotus	tarasea	n.c.v.
Bohadschia argus	vula	n.c.v.
Halodeima atra	loliloli	n.c.v.
Synapta maculata	?	n.c.v.

* = exploited in Laucala Bay.

o.m. = overseas market.

l.m. = local market.

n.c.v. = no commercial (or food) value.

Authorites for generic and specific names: Appendix IV.

3.3. Seagrass Community: Function.

Seagrass communities play an integral part in the nearshore ecosystem. Their generalized role was summarized by Wood et al. (1969):

(1) Seagrasses have an extremely high rate of growth and productivity. Production values of 500-1000gC $m^{-2}y^{-1}$ are typical (Zieman and Wetzel, 1980). Primary production is the most essential function (den Hartog, 1979)(this Section).

(2) The leaves support large numbers of epibiota which may be comparable in biomass with the above-ground biomass of the seagrass.

(3) Energetically the seagrasses act as a direct food source for grazing herbivores (e.g., turtle, fish, sea urchins and gastropods) although the efficiency with which the seagrass is digested is subject to much discussion (see Kikuchi, 1980; Ogden, 1980). Many animals graze extensively on the seagrass epiphytes in which case the seagrass blades may be ingested incidentally (Blaber, 1974; Kirkman, 1978). Most of the material produced by seagrasses is decomposed by microorganisms and utilized by macroconsumers through detritus food chains (Kikuchi, 1980).

(4) Seagrasses provide organic matter to initiate sulphate reduction and an active sulphur cycle.

(5) The seagrass leaves create a boundary layer reducing near bottom current velocities (Fonseca and Thayer, 1979, 1980). This prevents erosion and preserves the microbial biota of the sediment and sediment-water interface. The leaves also trap suspended sediment (Section 4) which is stablized and bound by the root+rhizome system (Ginsburg and Lowenstam, 1958).

(6) The seagrass community includes many carbonate producing organisms which, on death, contribute to the sediment by in situ deposition of skeletal debris (Burrell and Schubel, 1977).

(7) The more stable hydrodynamic environment amongst the seagrass blades offers shelter to many organisms (Section 3.2.3.). It is exploited as a spawning and nursery area, providing a diverse substrate, concealment from predators and an abundant supply of trapped organic matter.

3.3.1. Determination of Leaf Productivity of *S. isoetifolium*: Calculation Method.

The methods of determining production in seagrasses are the subject of a recent review by Zieman and Wetzel (1980). There are three basic methods: measurement of biomass by harvesting techniques; of growth by marking techniques; of net photosynthesis by metabolic techniques. Of these, the marking techniques (Zieman, 1968, 1974; Patriquin, 1973) "seem, at this time, to give the least ambiguous answers" (Zieman and Wetzel, 1980). The method is designed mainly for the determination of net leaf production although it was used to estimate underground production by Patriquin (1973).

The staple-marking technique of productivity measurement necessitated harvesting the marked leaves at the end of the experimental period (Zieman and Wetzel, 1980). New growth could then be separated from leaves present at the time of marking. Biomass of the respective parts was determined directly. Using the pin-marking technique developed in this study (Section 3.3.2) this approach was impractical; the pins were dislodged and lost as soon as the leaves were harvested. The leaves were also very prone to breakage.

In determining the productivity of *Zostera marina*, Jacobs (1979) counted the number of marked shoots that produced a new leaf during the observation period. He calculated the plastochrone interval (P.I.), i.e., the time interval between the initiation of two successive leaves on one shoot.

$$\text{P.I. (days)} = \frac{\text{number of shoots marked x observation period (days)}}{\text{number of new leaves on marked shoots}}$$

In this study the laborious pin-marking technique did not generate sufficient data to calculate the P.I. using this formula. However, using a variation of this formula in conjunction with detailed quadrat analysis of shoot and leaf counts, the productivity of *S. isoetifolium* was estimated. The procedure was as follows:

Leaf growth rates were measured by pin-marking techniques (Section 3.3.2.). Mean growth rate of newly emerged leaves, estimated to be ≦ 60mm long midway through the growth experiment, was determined (Section 3.3.2.2.). The average time for a leaf to grow to a length of 60mm (T_{60}) was calculated as:

$$T_{60} \text{ (days)} = \frac{60 \text{ (mm)}}{\text{mean growth rate of newly emerged leaves} \leqq 60\text{mm long (mm day}^{-1})}$$

It was then assumed that, within a given area, all the newly emerged leaves ≦ 60mm long had emerged within a preceding period of T_{60} days.

Quadrats of *S. isoetifolium* were analysed (Section 3.3.3.). The number of shoots m^{-2} and the average number of leaves shoot^{-1} were determined. The number of newly emerged leaves ≦ 60mm long was counted. The P.I. was calculated as:

$$\text{P.I. (days)} = \frac{\text{number of shoots m}^{-2} \text{ x } \begin{array}{c}\text{average time for a leaf to grow to}\\ \text{a length of 60mm } (T_{60}\text{, days})\end{array}}{\text{number of newly emerged leaves} \leqq 60\text{mm long m}^{-2}}$$

Turnover rate, i.e., the fraction of an organism or population that is produced per unit time (percent change per day) was then calculated (Jacobs, 1979) as:

$$\text{turnover (\% day}^{-1}) = \frac{1}{\text{P.I. x average number of leaves shoot}^{-1}} \text{ x } 100$$

This can also be expressed as a turnover period:

$$\text{turnover period (days)} = \frac{1}{\text{turnover (\% day}^{-1})} \text{ x } 100$$

S. isoetifolium leaf biomass was determined (Section 3.3.4.). The average carbon content of the seagrass was taken to be 47% of the organic (ash-free) dry weight (Westlake, 1963). Leaf productivity was then calculated as:

$$\text{leaf productivity (gC m}^{-2}\text{day}^{-1}) = \frac{\text{leaf biomass (g ash-free dry wt.)}}{\text{turnover period (days)}} \times 0.47$$

3.3.2. Leaf Growth.

Zeiman and Wetzel (1980) observed that the staple-marking technique (Zieman, 1968, 1974) is impractical to use with *S. isoetifolium*. They suggested that a non-water soluble marker pen as used by Sand-Jensen (1975), might be satisfactory. However, in order to blot the leaves prior to marking, Sand-Jensen had to excavate an eelgrass peat, place it in a box and lift it out of the water. For *S. isoetifolium* this approach has several drawbacks on account of the fragility of the leaves and the loose nature of the sediment. An in situ growth measurement technique was required.

The leaf-blade of *S. isoetifolium* is subulate (circular in cross-section) tapering upwards to a flattened, serrate, tip. Along the Suva Reef transect line, maximum leaf diameter decreased with increasing water depth, from 2.6mm at metre 15 (C.D. -0.8m) to 2.1mm at metre 95 (C.D. -3.2m). Minimum leaf diameter measured immediately below the flattened tip was 1.1 - 0.8mm. The measurement technique had to be sufficiently refined to avoid damaging the leaf but equally, robust enough that it could be performed by a diver.

Headless stainless steel entomological pins 150μm dia. x 15mm long were dipped into molten sealing wax and a head approximately 1.5mm dia. x 6mm long was moulded onto each. Finished pins were stored by placing them in strips of expanded foam rubber. With practice, a heavily over-weighted diver lying on the sea bed could accurately place the pins through the *S. isoetifolium* leaves. The procedure was laborious. In planning dive durations an estimate of 1 minute per pin inserted was used. A similar unit time was allocated for measuring the growth increment on the return visit. Dive times often exceeded 90 minutes, lying virtually motionless on the sea bed with current velocities of up to 0.3m s^{-1}. This technique required great concentration and steadiness of hand. Despite the comparatively warm water temperatures, 24-28°C, the major problem was the cold; full wetsuits with hoods were used. Field equipment comprised a weighted perspex board with pencils, ruler and plastic paper data sheets (ruled up using alcohol-based marker pens) attached. The foam strip holding the pins was tied to the board by a short length of string. The air trapped within the expanded rubber was sufficient to buoy it up, thus forming a readily accessible 'pin dispenser'. During preliminary experiments individual stems were marked by placing a nail with a numbered plastic label at the base of the sheath. For the main experiments 2 x 1m long lines were secured to the sea bed at each site. Pins were then placed in leaves chosen at random along the lines.

3.3.2.1. Preliminary Experiments: Leaf Growth Characteristics of *Syringodium isoetifolium.*

Pins were placed in 14 leaves to determine whether there was any elongation of the leaf after emergence from the sheath. 3 pins were placed in each leaf at intervals of approximately 30mm with the first pin (A) at the level of the top of the sheath (Fig. 3.3.2.1a). Leaves of varying length (36mm-385mm) and from several depths (C.D. -0.8m to C.D. -3.2m) were chosen.

33 inter-pin measurements were obtained (some pins were lost from the leaves during the experiment). Of these (Table 3.3.2.1a), 15 were

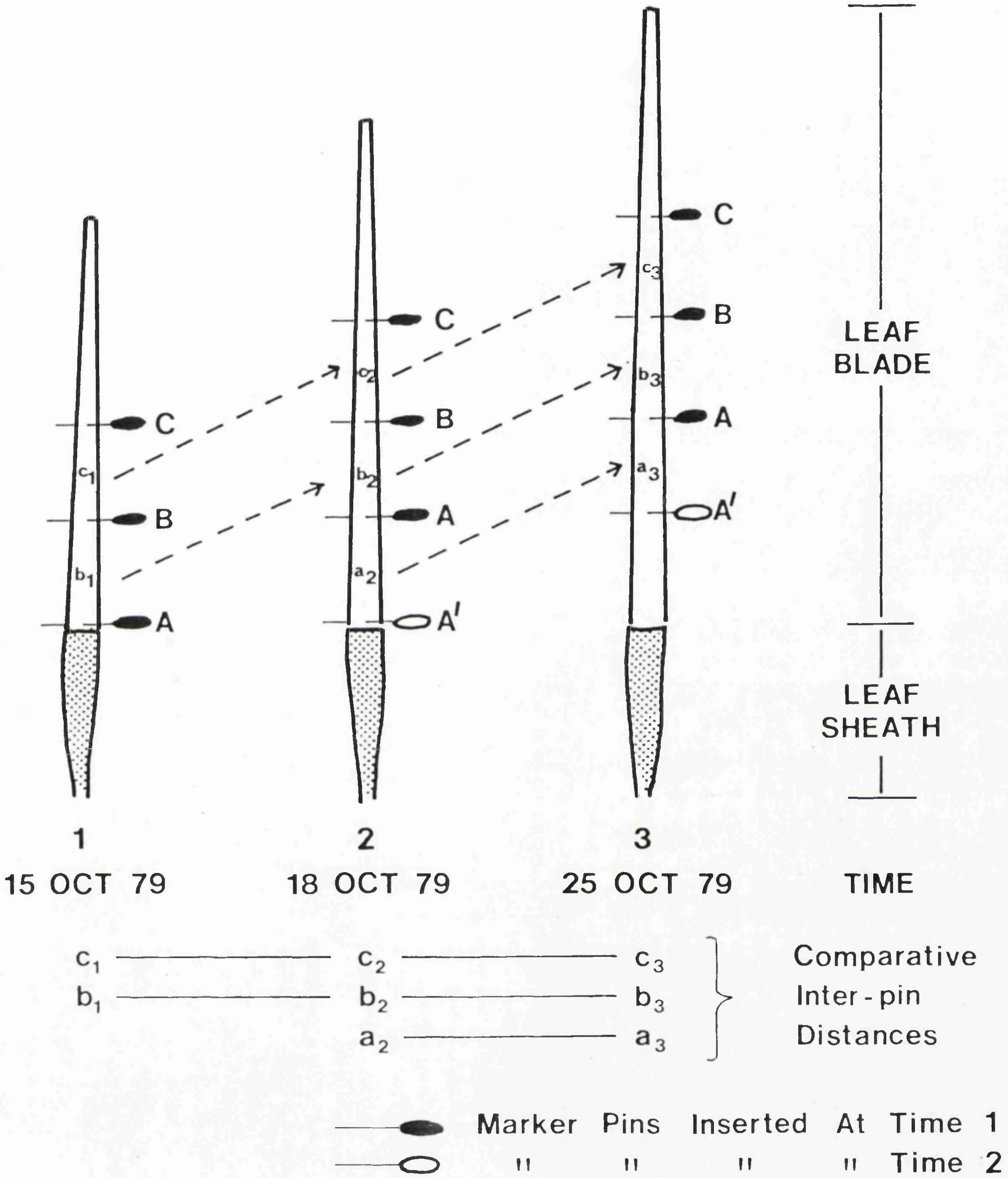


FIGURE 3.3.2.1a

Preliminary growth experiments with *Syringodium isoetifolium*. Positions of pins and comparative inter-pin distances.

TABLE 3.3.2.1a. RESIDUALS OF INTER-PIN DISTANCES MEASURED ON LEAVES OF *SYRINGODIUM ISOETIFOLIUM*.

Leaf No.	Residual of inter-pin distances, mm.					
	$a_3 - a_2$	$b_2 - b_1$	$b_3 - b_2$	$c_2 - c_1$	$c_3 - c_2$	TOTAL
1	.	0	.	-1	.	
2	.	0	.	.	.	
3	-1	-1	-1	.	.	
4	0	1	-1	.	.	
5	.	0	.	-2	.	
6	0	0	.	0	.	
7	-1	-1	.	.	.	
8	0	0	0	.	.	
9	1	4	-2	.	.	
10	0	0	.	1	.	
11	.	1	.	.	.	
12	-2	1	.	.	.	
13	.	1	0	0	0	
14	1	.	.	.	.	
n	9	13	5	5	1	33
$\bar{x}$	-0.22	0.46	-0.80	-0.40	0	-0.06
$\sigma n-1$	0.97	1.27	0.84	1.14	0	1.14

In all cases residuals are calculated as inter-pin distance (time t) minus inter-pin distance (time t - 1). See Figure 3.3.2.1a.

exactly the same on repeated measurement. Of the remainder, the maximum difference was 4mm (over a length of 43mm; 9%). The mean difference was -0.06mm (S.D. = 1.14mm) over a mean inter-pin distance of 33.9mm (S.D. = 9.0mm). It was concluded that there was no elongation of the leaf after emergence from the sheath. In all subsequent experiments one pin only was inserted; at the level of the top of the sheath.

Observations made during this experiment also confirmed that the narrowing of the base of the leaf-blade marks the termination of growth of that leaf. Profitting from this clear morphological division between growing and non-growing leaves, the *S. isoetifolium* leaves were categorized into three types (Fig. 3.3.2.1b).

A: non-growing, senescent, leaves with a narrowed base.

B: growing leaves from which the leaf-tip is absent on account of breakage or grazing.

C: growing leaves on which the leaf-tip is intact.

3.3.2.2. Leaf Growth Rates: Control Site, Suva Reef Transect Line, October, 1980, February, 1982.

Leaf growth (length) of *S. isoetifolium* was measured at metres 15, 55 and 95 along the Suva Reef transect line (Fig. 3.2.1.1a). In each experimental leaf a pin was inserted at the level of the top of the sheath. After 3 days the sites were revisited. The increase in leaf length (I), i.e., the distance from the top of the sheath to the pin, was measured (Fig. 3.3.2.2a). The length of the leaf (L_{obs}) and the presence or absence of the leaf-tip were recorded. Intact-tip leaves were separated from absent-tip leaves. The results in each category were ranked in ascending order of L, the estimated length of the leaf midway through the growth experiment; $L = L_{obs} - (\frac{I}{2})$. The duration of the experiment was expressed in terms of "light days", one "light day" being the interval

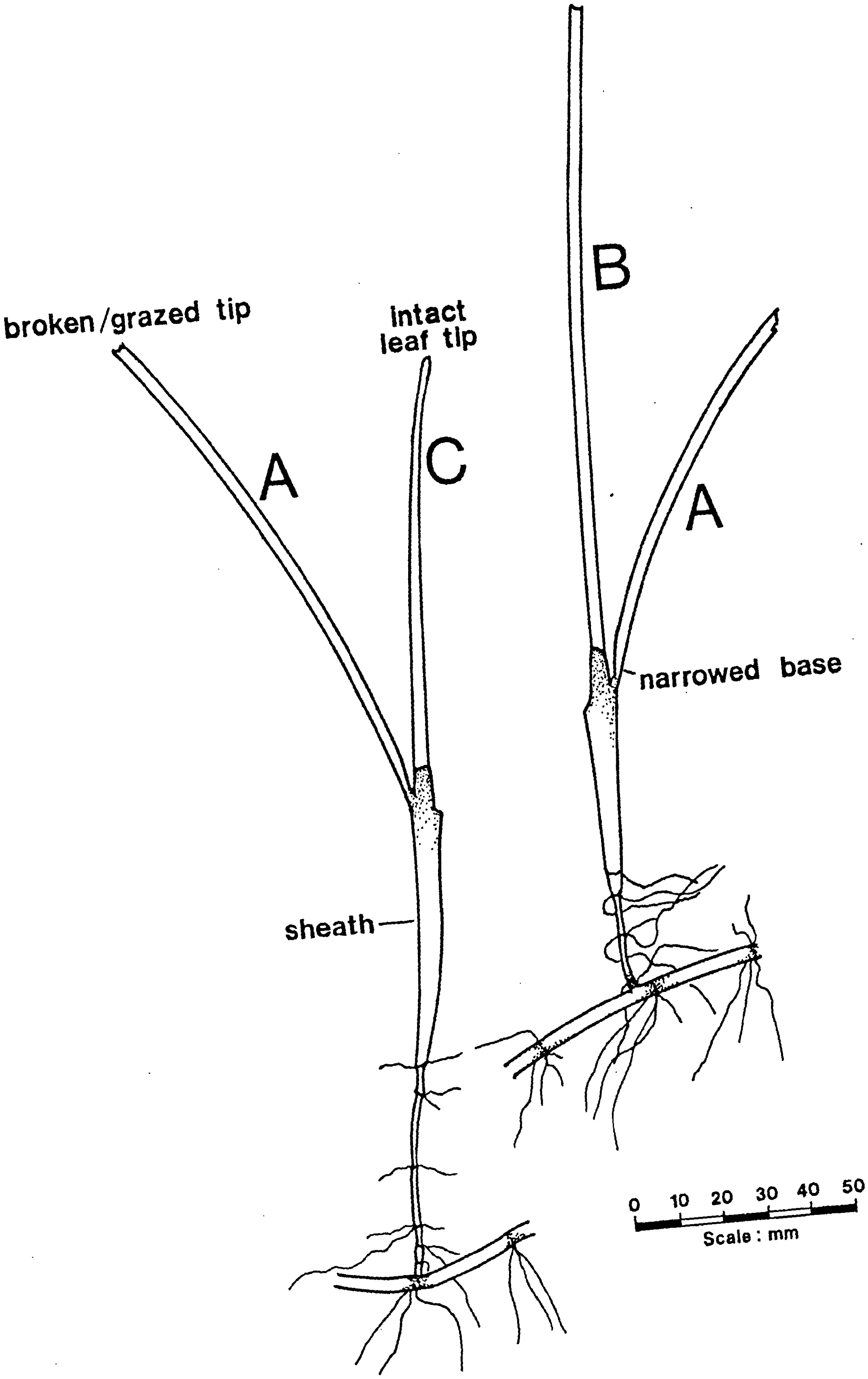


FIGURE 3.3.2.1b

Leaf types of *Syringodium isoetifolium*.

A : non growing, senescent, narrowed base
B : growing, broken/grazed leaf tip
C : growing, intact leaf tip

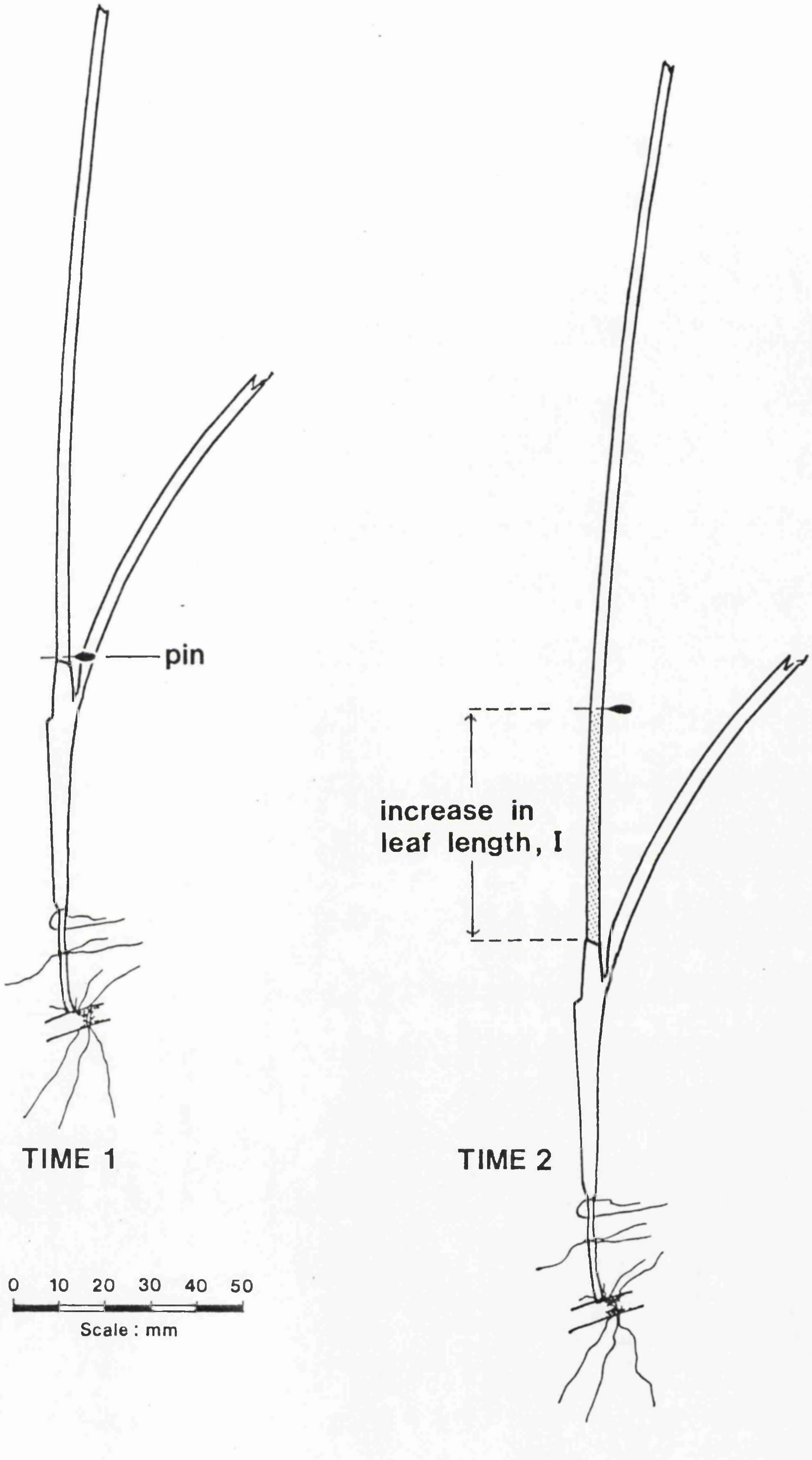


FIGURE 3.3.2.2.a

Measurement of leaf growth (increase in length) of *Syringodium isoetifolium* using a pin– marker.

between sunrise and sunset (Fiji Nautical Almanac, 1979, 1980). The increase in leaf length (I) was then expressed as a growth rate (GR), mm day^{-1}. Any leaf that developed a narrow base between marking and measurement was excluded from the analysis. Such leaves had stopped growing at an undetermined time during the observational period (see Section 3.3.3).

The first leaf growth measurements were made from 15-18 October, 1980 (Table 3.3.2.2a), the second from 23-26 February, 1982 (Table 3.3.2.2b). The combined data, leaf growth rate vs. L, were plotted (Fig. 3.3.2.2b). Mean leaf growth rates (MLGR) were then calculated for intact-tip leaves, the combined data and intact-tip leaves with L $\leqq$ 60mm (Table 3.3.2.2c).

During October, 1980 leaf growth rate ranged from 4.8 to 10.6mm day^{-1} averaging 7.9, 6.8 and 8.1mm day^{-1} at metres 15, 55 and 95 respectively (total 34 measurements). During February 1982 leaf growth rate ranged from 3.0 to 11.7mm day^{-1} averaging 5.9, 6.5 and 8.6mm day^{-1} at metres 15, 55 and 95 respectively (total 69 measurements). During both sets of observations the highest MLGR and the highest individual leaf growth rate were recorded from the deepest station, metre 95 (C.D. -3.2m). There was no overall increase or decrease between the October and February measurements; MLGR was 25% less at metre 15, 4% less at metre 55 but 6% greater at metre 95.

There was no significant difference between the average growth rate of leaves with intact tips and that of those without tips ($P > 0.05$). Nor was there any significant difference between the average growth rate of type C leaves $\leqq$ 60mm long (midway through the experiment) and that of all the leaves measured ($P > 0.05$).

3.3.3. Quadrat Analysis: Shoot and Leaf Counts.

Turfs of *S. isoetifolium*, 250mm x 250mm (0.0625m^2) were dug from the seagrass bed. In the laboratory all the shoots were cut at the level of

TABLE 3.3.2.2a. GROWTH RATES (mm day^{-1}) OF LEAVES OF *SYRINGODIUM ISOETIFOLIUM* BETWEEN 15 OCT (T_o) AND 18 OCT 1980 (T_1).

METRE 15				METRE 55				METRE 95			
Leaf-tip P		Leaf-tip A		Leaf-tip P		Leaf-tip A		Leaf-tip P		Leaf-tip A	
L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}
12	7.5	123	7.8	35	5.4	69	7.5	14	8.2	180	7.0
51	9.4	143	8.4	37	8.0	131	5.6	25	4.8	194	9.4
89	5.6	372	8.4	40	7.5	134	7.9	29	7.9	200	7.0
100	9.7			43	8.2	172	6.7	139	10.6		
138	4.1			51	6.4	179	6.1	213	10.0		
139	10.0			62	6.4	233	8.5				
				76	5.6						
				87	6.0						
				103	6.5						
				109	6.7						
				127	7.3						

Suva Reef transect line, metres 15, 55, 95 (See Fig. 3.2.1.1a). Leaves divided into those with leaf-tip present (P) and absent (A). Leaves ranked according to L, where $L = L_{obs} - (\frac{I}{2})$. L_{obs} is length of leaf at time T_1 and I is the increase in leaf length between time T_o and T_1. Line separates those leaves, with tips, where $L \leqq 60$mm.

TABLE 3.3.2.2b. GROWTH RATES (mm day^{-1}) OF LEAVES OF *SYRINGODIUM ISOETIFOLIUM* BETWEEN 23 FEB (T_o) AND 26 FEB 1982 (T_1).

METRE 15				METRE 55				METRE 95			
Leaf-tip P		Leaf-tip A		Leaf-tip P		Leaf-tip A		Leaf-tip P		Leaf-tip A	
L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}	L,mm	mm day^{-1}
24	7.0	31	8.0	21	6.3	15	6.3	79	11.3	39	11.7
25	5.7	37	3.0	23	5.3	15	5.0	91	9.0	47	7.3
30	5.0	68	5.3	34	3.7	33	9.3	115	11.0	110	5.3
33	8.0	68	3.7	42	8.0	67	7.0	136	8.7	112	7.7
34	5.3	88	4.0	48	9.7	70	7.3	142	9.7	138	6.7
40	8.7	91	4.0	52	4.3	73	5.7			143	9.0
42	5.0	104	4.3	61	8.7	74	8.0			143	6.7
49	7.0	112	5.3			82	6.3			151	9.0
		113	5.3			83	6.3			161	8.7
		117	6.3			91	6.3			165	8.3
		118	3.3			103	5.7			169	10.3
		122	5.7			107	5.0			213	8.3
		137	5.7			109	4.3			223	8.3
		146	7.0			111	8.0			228	9.7
		150	7.7			187	7.3			241	7.7
		161	7.3							276	6.0
		191	7.0								
		195	8.7								

For explanation see Table 3.3.2.2a and Figure 3.2.1.1a.

TABLE 3.3.2.2c. SUMMARY OF MEAN LEAF GROWTH RATES (MLGR) FOR *SYRINGODIUM ISOETIFOLIUM*, SUVA REEF TRANSECT LINE 15-18 OCT 1980 and 23-26 FEB, 1982.

	MEAN LEAF GROWTH RATE, mm day^{-1}							
	METRE 15		METRE 55		METRE 95		MEAN	
	Oct '80	Feb '82	Oct '80	Feb '82	Oct '80	Feb '82	Oct '80	Feb '82
L ≦ 60mm	8.45	6.46	7.10	6.22	6.97	No Data	7.51	6.34
Leaf-tip 'P'	7.22	6.46	6.73	6.57	8.30	9.94	7.42	7.66
Leaf-tip 'A'	8.20	5.64	7.05	6.52	7.80	8.17	7.68	6.78
All Data	7.88	5.90	6.84	6.54	8.11	8.59	7.61	7.01

From Tables 3.3.2.2a and 3.3.2.2b.

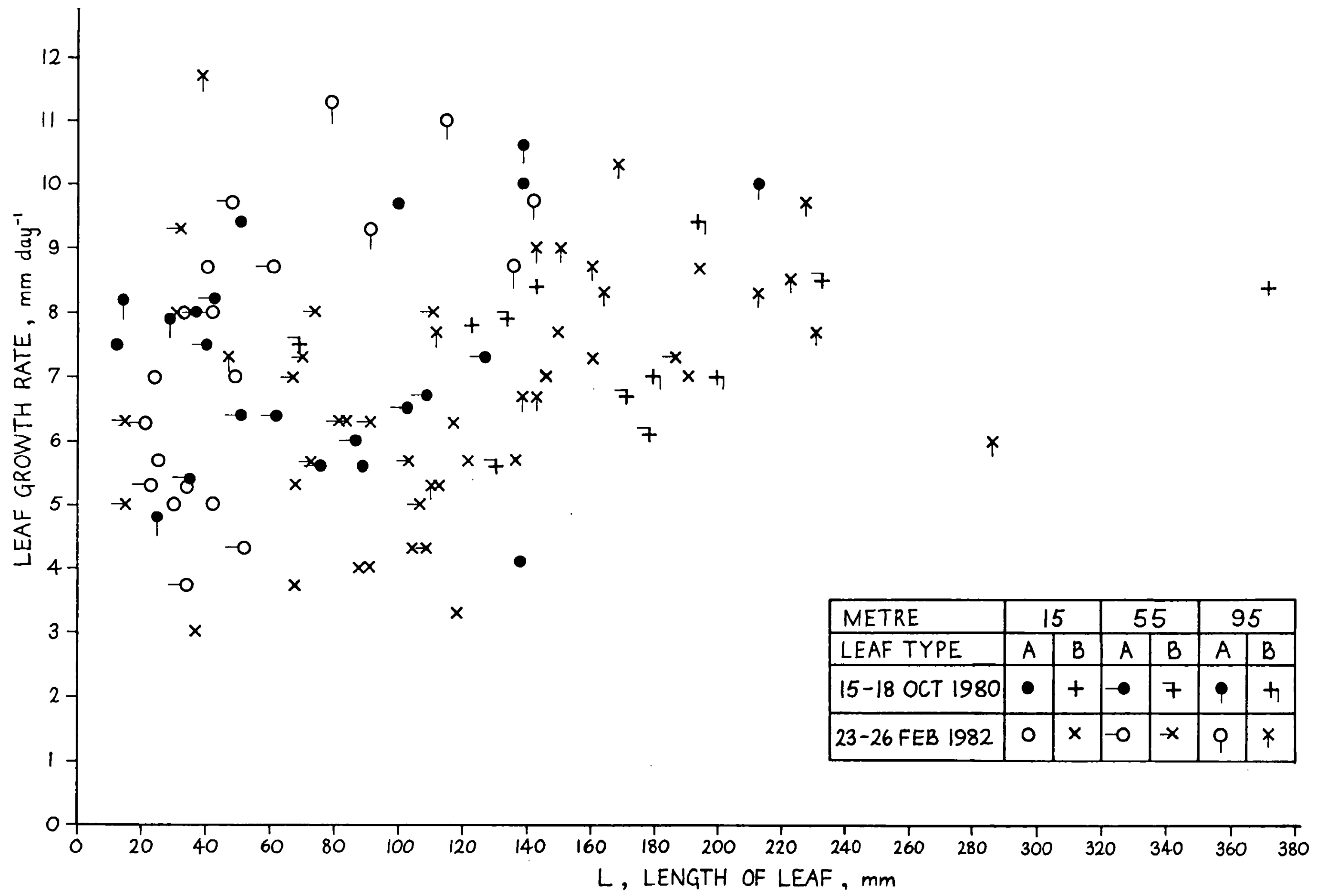


FIGURE 3.3.2.2b

Graph of leaf growth rate (increase in length) vs. length of leaf (mid-way through observational period). Based on field experiments at the Suva Reef transect line, metres 15, 55 and 95, in the periods 15 to 18 October 1980 and 23 to 26 February 1982.

the sediment surface. The leaves on each shoot (range 1-3) were then categorized into type A, B or C (Section 3.3.2.1). The length of each leaf was then measured using length classes of 20mm.

On 25th October, 1980 (leaf growth rate expt. 1) 3 turfs were dug from the Suva Reef transect line, 1 each at metres 15, 55 and 95. The leaves were categorized and measured (Table 3.3.3a). The procedure was repeated on 23rd Febuary 1982 (leaf growth rate expt. 2)(Table 3.3.3b). The number of shoots (m^{-2}), number of each type of leaves (m^{-2}) and total number of leaves (m^{-2}) were recorded. The number of newly emerged leaves ≤ 60mm long (m^{-2}) was calculated as the sum of the frequencies of the first three length classes (1-20mm, 21-40mm, 41-60mm) of type C leaves ($\times \frac{1}{0.0625}$ to convert to m^{-2}). The mean number of leaves $shoot^{-1}$ and the mean number of growing leaves (types B and C) $shoot^{-1}$ were calculated (Table 3.3.3c).

Shoot density decreased with increasing depth from a maximum of ca. 4400 shoots m^{-2} at metre 15 (C.D. -0.8m) to ca. 1000 shoots m^{-2} at metre 95 (C.D. -3.2m).

Density is zero where the *S. isoetifolium* ends at metre 107 (C.D. -3.8m)(Fig. 3.2.1.1a). There is no evidence of seasonal differences of a scale greater than the sampling error (see Section 3.3.4). Replicate quadrats were not analysed owing to lack of time.

On 25th October, 1980 the mean number of leaves $shoot^{-1}$ varied little between the sites, averaging 1.76 ± 0.01. By comparison, on 23rd February, 1982 the mean number of leaves $shoot^{-1}$ decreased with increasing depth from 1.64 to 1.38, averaging 1.50 ± 0.13.

The mean number of growing leaves $shoot^{-1}$ averaged 1.04 ± 0.02 on 25th October, 1980 and 1.01 ± 0.03 on 23rd February, 1982 (overall range 0.99-1.06). If, on average, each shoot has 1 growing leaf then, as soon as that leaf stops growing, another leaf must emerge from the sheath.

TABLE 3.3.3a. ANALYSIS OF *SYRINGODIUM ISOETIFOLIUM* LEAVES FROM 0.0625m² QUADRATS, SUVA REEF TRANSECT LINE, METRES 15, 55 AND 95. 25 OCTOBER 1980.

	NUMBER OF LEAVES QUADRAT^{-1} (0.0625m²)								
Suva Reef	METRE 15			METRE 55			METRE 95		
Leaf Type	A	B	C	A	B	C	A	B	C
Leaf Length (mm)									
1-20	5	9	19	7	4	18	6	1	1
21-40	18	19	26	17	5	34	7	3	3
41-60	22	8	18	19	9	27	11	8	2
61-80	21	10	17	20	6	14	7	5	3
81-100	24	13	19	27	15	21	4	7	3
101-120	26	17	10	20	13	10	1	6	3
121-140	24	15	15	17	12	9	4	4	3
141-160	21	16	4	16	20	2	1	4	
161-180	12	8	3	10	16	2	2	3	
181-200	15	14	1	5	8	1	1	1	
201-220	6	7		5	6			1	
221-240	3	7		2	3				
241-260	2	2		2					
261-280				1				1	
281-300									
301-320									
TOTALS	199	145	132	168	117	138	44	44	18

For location see Figure 3.2.1.1a. For description of leaf types, see Section 3.3.2.1.

TABLE 3.3.3b. ANALYSIS OF *SYRINGODIUM ISOETIFOLIUM* LEAVES FROM 0.0625m² QUADRATS, SUVA REEF TRANSECT LINE, METRES 15, 55 AND 95. 23 FEBRUARY 1982.

	NUMBER OF LEAVES QUADRAT^{-1} (0.0625m²)								
Suva Reef	METRE 15			METRE 55			METRE 95		
Leaf Type	A	B	C	A	B	C	A	B	C
Leaf Length (mm)									
1-20	9	11	35	5	6	10	1	1	3
21-40	9	9	22	6	2	12	4	1	4
41-60	15	9	23	14	5	11	1	3	3
61-80	14	6	12	11	8	14	5	3	2
81-100	26	27	10	10	13	6	2	2	2
101-120	21	20	4	11	19	1	2	4	2
121-140	18	34	4	6	7	1	4	7	2
141-160	16	24	3	8	7		3	8	3
161-180	19	18		2	12		1	1	
181-200	9	6		2	13		4	11	
201-220	5	6			7		2	6	
221-240	2	6						5	
241-260	2	1			1			1	
261-280					1			2	
281-300							1	2	
301-320							1	1	
TOTALS	165	177	113	75	101	55	31	58	21

For location see Figure 3.2.1.1a. For description of leaf types, see Section 3.3.2.1.

TABLE 3.3.3c. ANALYSIS OF *SYRINGODIUM ISOETIFOLIUM* SHOOTS AND LEAVES; SUVA REEF TRANSECT LINE, 25 OCTOBER 1980 AND 23 FEBRUARY 1982.

Suva Reef Transect Line Metre	Date	No. of Shoots m^{-2}	Number of Leaves m^{-2}				No. of Newly Emerged Leaves Type C. ≤60mm Long m^{-2}	Maximum Leaf Length (Observed) mm	Mean No. of Leaves $Shoot^{-1}$	Mean No. of Growing Leaves $Shoot^{-1}$
			Non-Growing A	Growing; Tip Absent B	Growing; Tip Intact C	Total A+B+C				
15	25 Oct 80	4352	3184	2320	2112	7616	1008	251	1.75	1.02
	23 Feb 82	4432	2640	2832	1808	7280	1280	247	1.64	1.05
55	25 Oct 80	3856	2688	1872	2208	6768	1264	233	1.76	1.06
	23 Feb 82	2496	1200	1616	880	3696	528	271	1.48	1.00
95	25 Oct 80	960	704	704	288	1696	96	269	1.77	1.03
	23 Feb 82	1280	496	928	336	1760	160	309	1.38	0.99

From counts of $0.0625m^2$ quadrats. Expressed as number m^{-2}. For location see Figure 3.2.1.1a. For leaf type descriptions, see Section 3.3.2.1.

This was evidenced during observations of leaf growth rate. As was noted in Section 3.3.2.2, the leaves that developed a narrow base between the times of marking and measurement were excluded from the leaf growth rate calculations. When marked, these leaves were type B (i.e., growing, tip absent), but at an undetermined time during the observational period they became type A (i.e., non-growing, tip absent). In every case that this was observed, a new leaf (type C) had emerged during the same period. At the time of measurement, T_1, leaf length (L_{obs}), increase in leaf length (I) before the leaf stopped growing and length (L_c) of the newly emerged type C leaf were recorded (Table 3.3.3d). Assuming first that (i) the emergence of the new leaf was synchronous with the cessation of growth of the old leaf, and (ii) the leaf growth rate was constant for leaves of all ages (Section 3.3.2.2), then the mean old+new leaf growth rate should tally with the MLGR of the seagrass leaves as a whole.

Mean old+new leaf growth rate =

$$\frac{\text{growth increment of old leaf (GI), mm + length of new leaf } (L_c)\text{, mm}}{\text{observation periods (days)}}$$

Mean old+new leaf growth rate was 7.9 ± 1.5mm day^{-1} (range 6.3-10.3mm day^{-1}, 7 obs$^{ns.}$) which compares favourably with a MGLR for February, 1982 of 7.0 ± 1.4mm day^{-1} (Table 3.3.2.2c). The mean ratio of growing leaves to shoots is in fact slightly greater than 1 (overall mean 1.03 ± 0.03). This would be consistent with the emergence of a new leaf shortly before the old leaf stops growing. A brief overlap would account for a marginal increase in the mean new+old leaf growth rate.

3.3.4. Biomass.

S. isoetifolium biomass was determined for areas where coverage was 100%. To convert to biomass m^{-2} for the seagrass meadow as a whole, including bare sand areas, transect data from Suva Reef were used (Section

TABLE 3.3.3d. MEASUREMENTS OF THE INCREASE IN LENGTH OF *SYRINGODIUM ISOETIFOLIUM* LEAVES IN SITUATIONS WHEN THE MARKED LEAF STOPPED GROWING AND A NEW LEAF WAS INITIATED DURING THE INTERVAL BETWEEN MARKING (T_o) AND MEASUREMENT (T_1).

Location and Date		Type B leaf, marked at time T_o. During interval T_o to T_1 leaf stopped growing. Type A leaf at time T_1.		Type C leaf initiated during interval T_o to T_1	Period of Observation $T_1 - T_o$ days	Combined increase in leaf lengths $I + L_c$ mm	Mean Leaf growth rate of combined leaf B/A and leaf C $\frac{I + L_c}{T_1 - T_o}$
		Leaf length at time T_1 L_{obs}, mm	Increase in leaf length I, mm	Leaf length at time T_1 L_c, mm			
	Metre 55	204	17	9	3.0	26	8.7
Suva		198	8	23	3.0	31	10.3
Reef		135	6	17	3.0	23	7.7
Transect		205	18	8	3.0	26	8.7
line		70	12	7	3.0	19	6.3
23-26	Metre 15	169	13	7	3.0	20	6.7
Feb 82		160	3	17	3.0	20	6.7

3.2.1.1). Combined biomass of the other 3 seagrass species in the meadows covering potential excavation sites was less than 1% of the *S. isoetifolium*. It was therefore not dealt with further.

0.0625m² turfs were cut from the seagrass bed by a diver using a metal quadrat and a diving knife. No attempt was made to remove sediment while underwater. The turf was placed in a polythene sack and taken ashore intact. In the laboratory, above- and below-ground parts were separated and the sediment carefully washed from the latter. The samples were blotted, weighed (wet weight), dried for 24 hours at 105°C, reweighed (dry weight), heated to 550°C for 1 hour in a muffle furnace (Dean, 1974) and again reweighed (ash weight). Biomass, in units of g ash-free dry weight m^{-2} was calculated as:

$$\text{biomass (g ash-free dry wt m}^{-2}\text{)} = \text{(dry wt - ash wt)} \times \frac{1}{0.0625}$$

In a second analysis the plants were further differentiated prior to weight determinations. The above-ground parts were divided into sheaths and leaves. The latter were separated into non-growing leaves, growing leaves with grazed or broken tips and intact growing leaves. These subsamples were analysed as above.

On 25th October, 1980 a total of 13 samples were collected from the Suva Reef transect line; at metres 15, 55 and 95 (Fig. 3.2.1.1a). 10 turfs were split into above- and below-ground parts. In the remaining 3, the above-ground parts were differentiated into 4 types.

Mean total biomass (g ash-free dry wt m^{-2}, above- and below-ground parts combined)(Table 3.3.4a) decreased with increasing depth: 343 ± 83 g m^{-2} at metre 15, the shallowest site (C.D. -0.8m), 232 ± 49 g m^{-2} at metre 55 (C.D. -1.2m) and 34 ± 12 g m^{-2} at metre 95, the deepest site (C.D. -3.2m). The ratio of above- : below-ground biomass for individual quadrats ranged from 0.73 to 1.20. Mean values for separate sites were

TABLE 3.3.4a. BIOMASS OF *SYRINGODIUM ISOETIFOLIUM* DIVIDED INTO ABOVE- AND BELOW-GROUND PARTS.

		ABOVE-GROUND LEAF+SHEATH				BELOW-GROUND ROOT+RHIZOME				TOTAL BIOMASS	
Locn.	No.	Wet Wt. g m^{-2}	Dry Wt. 105°C g m^{-2}	Biomass Ash-Free Dry Wt. g m^{-2}	Biomass: Wet Wt. Ratio	Wet Wt. g m^{-2}	Dry Wt. 105°C g m^{-2}	Biomass, Ash-Free Dry Wt. g m^{-2}	Biomass: Wet Wt. Ratio	Ash-Free Dry Wt. g m^{-2}	Above:Below Ground Ratio
15	1	2756	252	142	0.051	1987	233	118	0.059		1.20
15	2	3676	-	-	-	3067	422	168	0.055		-
15	3	4257	379	210	0.049	3541	419	216	0.061		0.97
$\bar{x}$				176				167		343	1.08
σ				48				49		83	
55	1	1497	130	70	0.047	1752	225	96	0.055		0.73
55	2	2514	220	121	0.048	1966	211	130	0.066		0.93
55	3	2382	225	111	0.047	1944	244	117	0.060		0.95
55	4	2612	235	126	0.048	2724	356	157	0.057		0.80
$\bar{x}$				107				125		232	0.85
σ				25				26		49	
95	1	227	19	10	0.043	170	24	10	0.061		1.00
95	2	417	38	21	0.051	379	61	20	0.054		1.05
95	3	549	-	-	-	379	55	24	0.063		-
$\bar{x}$				15				18		33	1.02
σ				8				7		12	
$\bar{x}$					0.048				0.059		0.95
σ					0.003				0.004		0.14

Determined by analysis of 10 x 0.0625m² quadrats. Suva Reef transect line. 25 October, 1980. See also Figures 2.1a (location) and 3.2.1.1a (transect profile).

1.08 at metre 15, 0.85 at metre 55 and 1.02 at metre 95. The overall mean was 0.95. The ratio of biomass : wet weight was calculated. For the above-ground parts the value was 0.048 ± 0.003, for the below-ground, 0.059 ± 0.004. These values are of interest, particularly the standard deviations.

The process of biomass determination was laborious: a reliable wet weight to biomass conversion was therefore expedient. The standard deviation of the above-ground biomass : wet weight ratios, *expressed as a percentage of the mean ratio*, is 6.25%. For each sampling site (3 or 4 replicates) the standard deviation of the above-ground biomass values was expressed as a percentage of the mean: 27.3%, 23.4% and 53.3% for metres 15, 55 and 95 respectively (Table 3.3.4a, column 3, means and S.Ds.). Similar calculations for the below-ground parts give values of 6.8% compared to 29.3%, 20.8% and 38.9%). Therefore, the errors likely to be incurred in conversion of wet weight to biomass are dwarfed by the unavoidable error incurred in the biomass determination technique.

Of the differentiated above-ground parts 43.8 - 54.9% comprised leaves, the remainder, sheaths (Table 3.3.4b). The leaf biomass : sheath biomass ratio was used to divide the mean above-ground biomass (Table 3.3.4a) into mean leaf and mean sheath biomass (Table 3.3.4c). Of the leaves, those actively growing comprised 54.3% of the total leaf biomass (mean of all sites, range 47.6 - 62.9%), those senescent, 45.7%.

On 23rd February, 1982, 3 x $0.0625 m^2$ turfs were dug from the Suva Reef transect line, 1 each from metres 15, 55 and 95. These were separated into above- and below-ground parts and weighed wet (blotted). Biomass of the leaves, sheaths and roots+rhizomes was calculated using the wet weight : biomass and leaf biomass : sheath biomass ratios derived in Tables 3.3.4a and 3.3.4b respectively.

TABLE 3.3.4b. BIOMASS OF *SYRINGODIUM ISOETIFOLIUM* DIVIDED INTO FOUR ABOVE-GROUND AND ONE BELOW-GROUND COMPONENTS.

Suva Reef Transect Line Metre		ABOVE-GROUND						BELOW-GROUND	Total Above and Below Ground	Ratio Leaf Biomass: Sheath Biomass
		Leaves				Sheaths	Total Above Ground	Roots and Rhizomes		
		Non-growing A	Growing; Tip Absent B	Growing Tip Intact C	Total Leaves A+B+C					
15	Biomass g m^{-2}	38.1	26.1	8.5	72.7	93.2	165.9	267.2	433.1	
	%	8.8	6.0	2.0	16.8	21.5	38.3	61.7	100.0	0.78
55	Biomass g m^{-2}	28.0	20.0	6.6	54.6	49.4	104.0	139.8	243.8	
	%	11.5	8.2	2.7	22.4	20.3	42.7	57.3	100.0	1.10
95	Biomass g m^{-2}	3.7	5.1	1.1	9.9	8.2	18.1	17.6	35.7	
	%	10.3	14.4	3.1	27.8	22.9	50.7	49.3	100.0	1.21
Plant Components As % Total Plant Biomass Mean %		10.2	9.5	2.6	22.3	21.6	43.9	56.1	100.0	
Leaf Types as % Total Leaves		45.7	42.6	11.7	100.0					
Mean										1.03

Determination as for Table 3.3.4a.

TABLE 3.3.4c. SUMMARY OF *SYRINGODIUM ISOETIFOLIUM* BIOMASS (g ASH-FREE DRY WEIGHT m^{-2}) DATA.

Suva Reef Transect Line Metre	Date	ABOVE-GROUND				BELOW-GROUND		Total Biomass g Ash-Free Dry Wt. m^{-2}
		Wet Wt. g m^{-2}	Above-Ground Biomass	Leaf Biomass	Sheath Biomass	Wet Weight	Root+Rhizome Biomass	
15	25 Oct 80		176	77	99		167	343
	23 Feb 82	3376	162	71	91	2160	127	289
55	25 Oct 80		107	56	51		125	232
	23 Feb 82	1680	81	42	39	1344	79	160
95	25 Oct 80		15	8	7		18	33
	23 Feb 82	832	40	22	18	335	20	60
MEAN	25 Oct 80			47	52		103	202
	23 Feb 82			45	49		75	169

Above- and below-ground biomass from Table 3.3.4a. 23 February 1982: wet weights from analysis of 0.0625m^2 turfs, above- and below-ground biomass estimated using biomass:wet weight ratios of 0.048 and 0.059 respectively (Table 3.3.4a). Above-ground biomass divided into leaf biomass and sheath biomass using ratios of 0.78, 1.10 and 1.21 for metres 15, 55 and 95 respectively (Table 3.3.4b).

The overall (all sites) mean total (above- and below-ground) biomass (ash-free dry wt.) was 202 g m^{-2} on 25th October, 1980, 169 g m^{-2} on 23rd February, 1982; a reduction of 16%. This reduction was largely due to a difference of 27% in the root+rhizome biomass. The overall mean leaf biomass and sheath biomass showed a drop of 4% and 6% respectively.

3.3.5. Leaf Productivity of *S. isoetifolium.*

Leaf productivity was calculated (method; see Section 3.3.1.) for *S. isoetifolium* at the Suva Reef transect line, metres 15, 55 and 95, for the periods 15-18th October, 1980 and 23-26th February 1982 (Table 3.3.5a).

Maximum leaf productivity, 0.62 gC $m^{-2}day^{-1}$, was observed at metre 15 (C.D. -0.8m). In both experiments leaf productivity decreased with increasing depth, reaching zero at the depth limit of the *S. isoetifolium* (metre 107, C.D. -3.8m). There was no clear pattern of difference between leaf productivity in October, 1980 to that in Febuary, 1982. There was a decrease of 5% and 40% at metres 15 and 55 respectively and an increase of 333% at metre 10. These fluctuations are largely a function of the difference in leaf biomass values.

The value of most meaning for this study was the leaf productivity of the seagrass meadow as a whole. MLGR, number of shoots m^{-2}, number of type C leaves ≦ 60mm long m^{-2}, average number of leaves $shoot^{-1}$ and leaf biomass were averaged for metres 15, 55 and 95. From these mean values, mean T_{60}, P.I., T.R. and T.P. were calculated, arriving at a value of mean leaf productivity for *S. isoetifolium* (100% cover)(Table 3.3.5a). Percentage cover of *S. isoetifolium* was estimated to be 62% on 30th October, 1980, 55% on 19th March, 1982 (Table 3.2.1.1a). The mean leaf productivity for the seagrass meadow was then calculated: 0.25 g C $m^{-2}day^{-1}$ (15-18th October, 1980) and 0.21 g C $m^{-2}day^{-1}$ (23-26th February, 1982).

TABLE 3.3.5a. CALCULATION OF *SYRINGODIUM ISOETIFOLIUM* LEAF PRODUCTIVITY (g C m^{-2} day^{-1}).

SOURCE TABLE NO.		3.3.2.2c		3.3.3c			3.3.3c			3.3.4c	
ABBREVIATION		MLGR	T_{60}			P.I.		T.R.	T.P.		
Date	Locn. on Suva Reef Transect Line	Mean Leaf Growth Rate mm day^{-1}	Time for Leaf to Grow to 60 mm days	Number of Shoots m^{-2}	Number of Type C Leaves ≦60mm long m^{-2}	Plasto-Chrone Interval days	Average Number of Leaves $Shoot^{-1}$	Turnover Rate % day^{-1}	Turnover Period days	Leaf Biomass g Ash-Free Dry Wt m^{-2}	Leaf Productivity, 100% Cover g C m^{-2} day^{-1}
15-18 Oct 1980	15	7.9	7.6	4352	1008	33	1.75	1.7	58	77	0.62
	55	6.8	8.8	3856	1264	27	1.76	2.1	48	56	0.55
	95	8.1	7.4	960	96	74	1.77	.8	131	8	0.03
	MEAN	7.6	7.9	3056	789	31	1.76	1.8	55	47	0.40
23-26 Feb 1982	15	5.9	10.2	4432	1280	35	1.64	1.7	57	71	0.59
	55	6.5	9.2	2496	528	43	1.48	1.6	64	42	0.31
	95	8.6	7.0	1280	160	56	1.38	1.3	77	22	0.13
	MEAN	7.0	8.6	2736	656	36	1.50	1.9	54	45	0.39

For calculation of T_{60}, P.I., T.R., T.P. and leaf productivity, refer to Section 3.3.1. Mean T_{60}, P.I., T.R., T.P. and leaf productivity calculated from mean values of MLGR, number of shoots m^{-2}, number of type C leaves ≦ 60mm long m^{-2}, average number of leaves $shoot^{-1}$ and leaf biomass.

In the region extending from Nukulau Island to Namuka Island, the seagrass meadows cover an estimated 187.2 ha (Table 1.4.2a) with an overall mean leaf productivity of 0.23 g C $m^{-2}day^{-1}$ (this Section). From these figures the mean annual leaf productivity of *S. isoetifolium* in the study area was calculated to be 157 tonnes C y^{-1}.

Mean P.I. increased from 31 days in October, 1980 to 36 days in February, 1982. However, on account of the smaller average number of leaves $shoot^{-1}$, the turnover period in February, 1982 was 54 days by comparison to 55 days in October, 1980.

It has been noted (this Section) that for *S. isoetifolium*, the P.I. is a measure of the average number of growing days for a leaf. The predicted average leaf length was calculated as MLGR x P.I. (overall means). For the period 15-18th October, 1980, the predicted average leaf length was 236mm; for the period 23-26th February, 1982, 252mm. These values are not inconsistent with the observed maximum leaf lengths of 233-269mm and 247-309mm for the respective periods.

3.4. Seagrass Community: Dynamics.

Studies of the structure and function of the seagrass community deal with the composition and activities of the community during the observational period. However, the community is liable to change. In an established meadow, where steady-state (den Hartog, 1977) has been achieved, natural changes in the vegetation pattern are likely to be either seasonal or caused by temporary disturbances: e.g., conditions of high wave energy impinging on a normally lee shore, freshwater stress due to flooding or desiccation on an extreme low spring tide. Potentially more severe than these perturbations are man-made changes. The sand dredging in Fiji is an example of one of the most extreme man-made effects: complete excavation of sections of the seagrass meadow. This is not the only human influence on the reef; land clearance and industrial pollution, for instance, may have equally deleterious effects (Section 1.5.). Subsequent to any man-made changes a seagrass community may develop, by the process of succession, until a new (but probably different) steady-state is restored. Alternatively, it may be that the new conditions are unsuitable for re-establishment of seagrass. Another type of community may develop naturally or be created artificially (Section 3.7.).

3.4.1. Recovery of the Dredged Areas.

During 1976-1977, 14 years after the commencement of sand extraction, many of the sites first to be dredged were reworked. Thus, from the information supplied by Fiji Industries Ltd. (Table 1.4.2a) the pit untouched for the maximum length of time is Waiqanaki II, dredged during 1973. Excavations in Waiqanaki I and III continued until 1976 and 1977 respectively. The Nukubuco Reef pits were started in 1977 and continued throughout the study period. No areas dredged between 1962 and 1973 were left untouched by the reworking of the sand deposits.

Immediately after excavation the pit slopes are very unstable (Section 4.3). As the slopes become less steep, the remaining seagrass beds are undercut. This provides a source of turfs of *S. isoetifolium* that lodge on the slopes and at the bottom of the dredge pits. However, none were observed to survive over a period of years. Those found in Waiqanaki III during 1980 had disappeared by 1982.

The pioneer seagrass species *Halophila minor* was found in all the dredge pits down to a depth of 11m below C.D. It was particularly abundant in dredge pit Waiqanaki II which was excavated only to a depth of 5-7m below C.D.

On the 'oldest' dredge pit floors crustacean mounds characteristic of the open sand community (Section 3.6) were found. The only other element of this community found in the pits was the holothurian *Microthele fuscogilva*. A few other species were periodically observed in the dredge pits; the holothurian *Actinopyga crassa*, the starfish *Mithrodia clavigera* and *Acanthaster planci* and the anemone *Actinodendron plumosum*. These animals had been swept into the dredge pit and except for the anemone (which thrived) were unsuited to the environment. The dredge pit floor provides little in the way of food or shelter. No resident or nursery species of fish were observed. The water column was usually devoid of fish: the only species seen were an occasional trevally or red mullet.

The most striking feature of the Waiqanaki dredge pits was the growth, on any available solid surface, of coral colonies. In many cases these were growing on debris inadvertently left behind after sand dredging: pieces of cable, metal hooks, etc. The corals were most abundant in dredge pit Waiqanaki II where *Acropora* spp., *Goniopora* sp., *Seriatopora hystrix* and *Montipora* sp. were found at depths of 5.0-6.1m below C.D. The colonies were 0.2-0.6m in diameter. In dredge pit Waiqanaki III a colony of *Acropora* sp., ca. 0.3m diameter, was found attached to a piece of cable protruding from the sea bed (Plate 3.7.2.1a).

3.4.2. Regenerative Potential of *Syringodium isoetifolium.*

Vegetative growth is of two kinds: serial production of new leaves (and associated root+rhizome growth) on one shoot (Section 3.3.1) and production of new shoots (lateral growth).

An opportunity to observe the rate of seagrass infilling within an established meadow was afforded by re-examination of concrete blocks installed along the Suva Reef transect line during 1980. The concrete blocks (exposed surface area: 0.0961m^2) were installed at 10m intervals, flush with the substrate. They were completely cleaned off on 23rd August, 1980 and remained undisturbed until 16th February, 1982 (18 months interval) when all the seagrass overgrowing the blocks was removed to the laboratory for analysis (Table 3.4.2a). The maximum biomass (above- + below-ground; ash-free dry wt.) was 193 g m^{-2} and compares with a mean biomass of 232-343 g m^{-2} for the seagrass meadow in that zone (Table 3.3.4a).

3.5. Seagrass Community: History and Classification.

The historical aspect of the seagrass community deals with the origin and development of seagrasses, resulting in the present day systems. One subject belonging to this category is the geographical distribution of seagrasses. On account of geographic and oceanographic isolation (Fiji lies 800km distant and upcurrent of its western neighbours), Fiji lies outside the Indo-West Pacific area of high species diversity. There are 6, probably 7, seagrass genera in New Caledonia and Vanuatu (den Hartog, 1977), only 3 in Fiji (Section 3.2.1). In the absence of the more competitive flat leaved genera (*Thalassia*, *Enhalus*, *Cymodocea)*, *Syringodium isoetifolium* is the dominant species in Fiji. The classification of communities is based largely on the structural elements (the species composition), to lesser extent on function and dynamics. The community in Fiji is restricted in number of species; it is therefore exceptional and cannot be ascribed to one of the broad alliances set up by den Hartog (1977).

3.6. The Open-Sand Community.

The open-sand community is mainly in water deeper than the lower depth limit of *S. isoetifolium.* The sea bed topography is characterised by mounds of sand (carbonate), 0.3-0.6m from trough to peak, thrown up by burrowing crustaceans (unidentified). There are sparse areas of *Halophila minor* and, in places, the substrate is completely covered by a

TABLE 3.4.2a. INFILLING BY *SYRINGODIUM ISOETIFOLIUM* OVER CONCRETE BLOCKS, SUVA REEF TRANSECT LINE, METRES 10-90.

Suva Reef Transect Line Metre	Biomass, g ash-free dry wt m^{-2}			Maximum Leaf length mm
	Leaf+Sheath	Root+Rhizome	Total	
10	73	81	154	190
20	31	31	62	190
30	102	91	193	210
40	54	57	111	180
50	8	18	26	110
60	-	-	-	-
70	14	14	28	210
80	6	6	12	160
90	3	5	8	170

For location see Figure 3.2.1.1a.

Exposed area of each concrete block = $0.0961m^2$.

Biomass calculated from wet weight using ratio of 0.048 for above-ground, 0.059 for below-ground parts (Table 3.3.4a). Expressed as g ash-free dry wt. m^{-2}.

blue-green algal mat. The macrofauna is scarce, comprising conspicuously large individuals and apparently few juveniles. Two asteroids, *Pentaceraster* sp. and *Choriaster granulosum*, are found in this zone. The former attains a diameter of 0.4m. The highly mobile echinoid *Astropyga radiata*, up to 0.3m in diameter, was seen periodically, sometimes in groups of 30 or more. Two holothurians are common to this area: the dendrochirotid, *Neothyonidium* sp. and the aspidochirotid *Microthele fuscogilva*. The former filters suspended organic matter from the lagoonwards flowing currents and can withdraw completely below the seabed if disturbed. Sea pens (Pennatulacea) were also found in this area, invariably orientated orthogonally to the incursive currents; they, too, have the ability to rapidly withdraw below the surface.

3.7. Dredge Pit Rehabilitation.

Towards the end of the first fieldwork period (March, 1979 to October, 1980), dredge pit Waiqanaki III was chosen as the site of pilot rehabilitation measures. The short term results of these preliminary experiments were assessed during the second fieldwork period (February - June, 1982).

3.7.1. Seagrass Transplantation.

Throughout the world, increased coastal engineering activities have inevitably damaged seagrass ecosystems. Recent research has been directed to replanting seagrass in affected areas. Transplanting methods were reviewed by Phillips (1980b). Knight et al. (1980) reviewed the literature.

There are no published records of transplants of *S. isoetifolium*. On the eastern seaboard of North America, *S. filiforme* has been successfully transplanted using the plug method (van Breedveld, 1975). Seeding and sprig planting techniques were not suitable for this species. The cost of transplanting seagrasses has been high. Most seagrass has been transplanted by wading in water less than 1m deep, a small amount using SCUBA. According to the method used, density of transplants and local conditions, costs for *Thalassia* and *Zostera* have ranged from US$4,000 - 550,000 ha^{-1} (Phillips, 1980c).

3.7.1.1. *S. isoetifolium* Transplants I: Waiqanaki III, October, 1980.

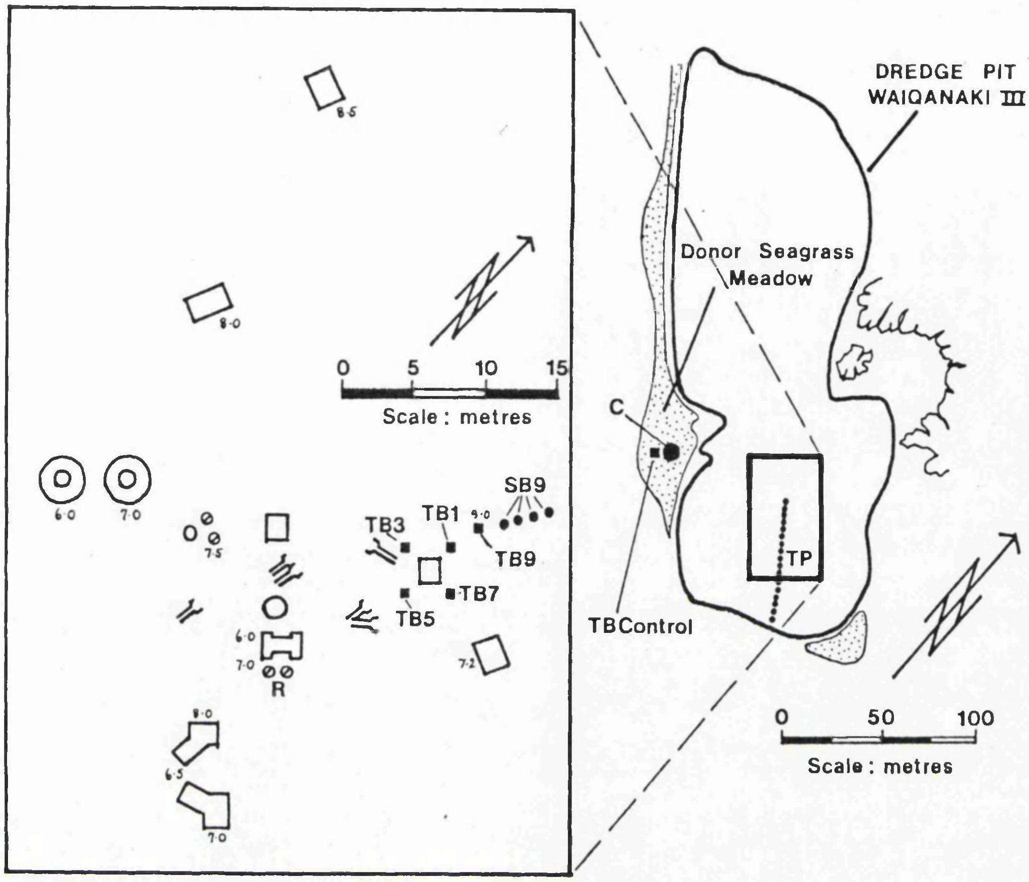
On 17th October, 1980, 20 seagrass turfs, ca. 250 x 250mm, were dug from the seagrass meadow at the western edge of dredge pit Waiqanaki III (Fig. 3.7.1.1a)(depth, C.D. -1.0m). Each was placed in a polythene sack, lifted out of the water and stored in a large plastic dustbin in the boat. Within an hour the turfs were transplanted on the slope and floor of the dredge pit at depths of 5.3 - 7.2m below C.D. (Fig. 3.7.1.1a). Each turf was dug in flush to the substratum.

During February, 1981 the site was revisited by M.L. Guinea who reported that no trace remained of the seagrass transplants. When reexamined during February, 1982 there was no sign of either transplanted or naturally recolonized *S. isoetifolium* (Section 3.2.1.1) on the dredge pit floor.

3.7.1.2. *S. isoetifolium* Transplants II: Waiqanaki III, March - June, 1982.

During March, 1982 a second attempt was made at transplanting *S. isoetifolium* in dredge pit Waiqanaki III. By inclusion of controls, the experiment was designed to measure (i) any detrimental effects, to the seagrass, of transplantation (ii) any changes in leaf growth rate following relocation of transplants to several deeper depths in the dredge pit (iii) the feasibility of transplantation as a rehabilitation procedure.

28 seagrass turfs 140 x 140mm were dug from the donor area (Fig. 3.7.1.1a). 24 of these were placed in 6 polystyrene boxes as used for packing 4 x 5dm^3 acid Winchesters. Each box measured 330 x 330mm x 200mm



depths in metres below C.D.

17 October 1980

TP ...... 250 x 250mm turfs in dredge pit floor

23 March 1982

▪ transplant boxes; TB1,3,5,7,9, Control

• transplants in dredge pit floor; SB9

● control area in seagrass meadow; C

26 March 1982

⊘ transplants in dredge pit floor, protected by fish exclusion cages:

R = by artificial reef

O = in open area

FIGURE 3.7.1.1a

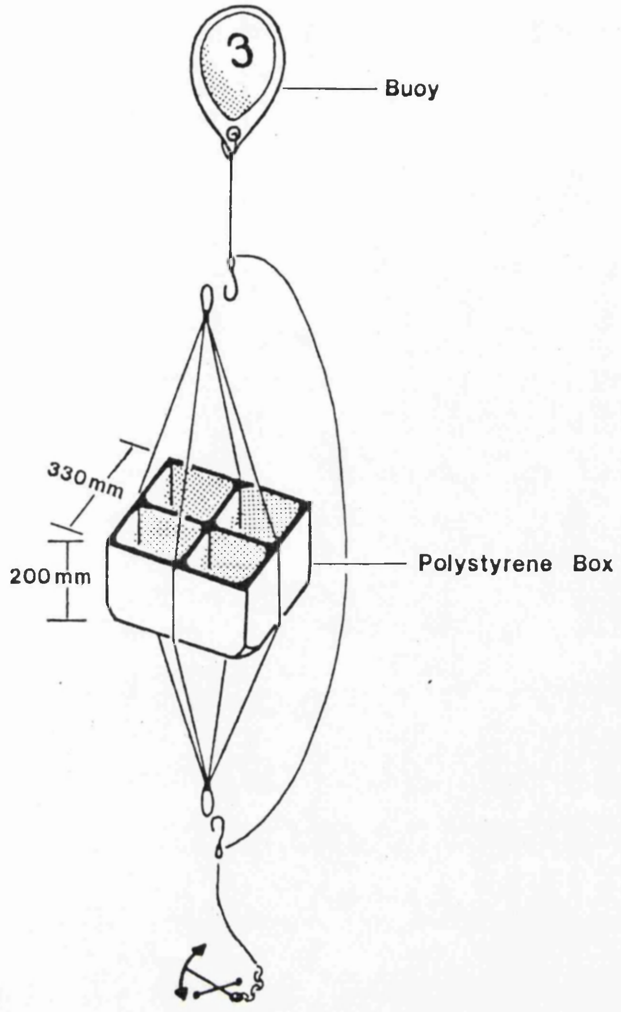
Location of seagrass transplants at dredge pit Waiqanaki III.
17 October 1980, 23 and 26 March 1982.
See also Figure 3.7.2.1a for description of artificial reefs and Plate 1.1a for location of dredge pit.

deep with four internal sections each 140 x 140mm. 4 of the boxes were suspended top and bottom by a cradle of 4 lines joining at a loop (Fig. 3.7.1.2a). With the turfs in place each box was neutrally buoyant and easily handled by a diver. Four lines,each with 2 metal hooks, extended vertically by 10dm^3 buoys, were anchored onto a concrete culvert (see Fig. 3.7.1.1a) on the dredge pit floor at 9.0m below C.D. The transplant boxes (TB) were then looped top and bottom onto the hooks on the line. In this way they were suspended at levels of 1, 3, 5 and 7m below C.D. These transplant boxes were coded TB1, TB3, TB5 and TB7 respectively. 4 seagrass turfs were transplanted directly into the sea bed at 9m below C.D.; coded SB9. A transplant box (TB9) was dug in alongside. The sixth transplant box (TBControl) was dug into the seagrass bed, flush with the sediment surface, alongside a marked control area of undisturbed seagrass (C).

Leaf growth rate was measured by the pin marking technique (Section 3.3.2). 25 leaves were marked in each transplant box. The suspended boxes were unhooked and brought to the boat for marking and measurement. All other work was carried out in situ. The experiment was initiated on 23rd March, 1982 and leaf growth was measured after 3 days on 26th March (day 0-3). One week after transplantation, leaf growth measurements were repeated (day 7-10; 30th March - 2nd April, 1982). The numbers of leaves measured and mean leaf growth rates (MLGR) are shown in Table 3.7.1.2a (full results; Appendix III).

At the outset, it was intended that the leaf growth rate measurements should be continued at 7-day intervals over an 8-week period. In the event, the experiment came to a premature end on account of an unforeseen factor: grazing of the transplants.

Disturbance of the seagrass beds led to displacement of infaunal and



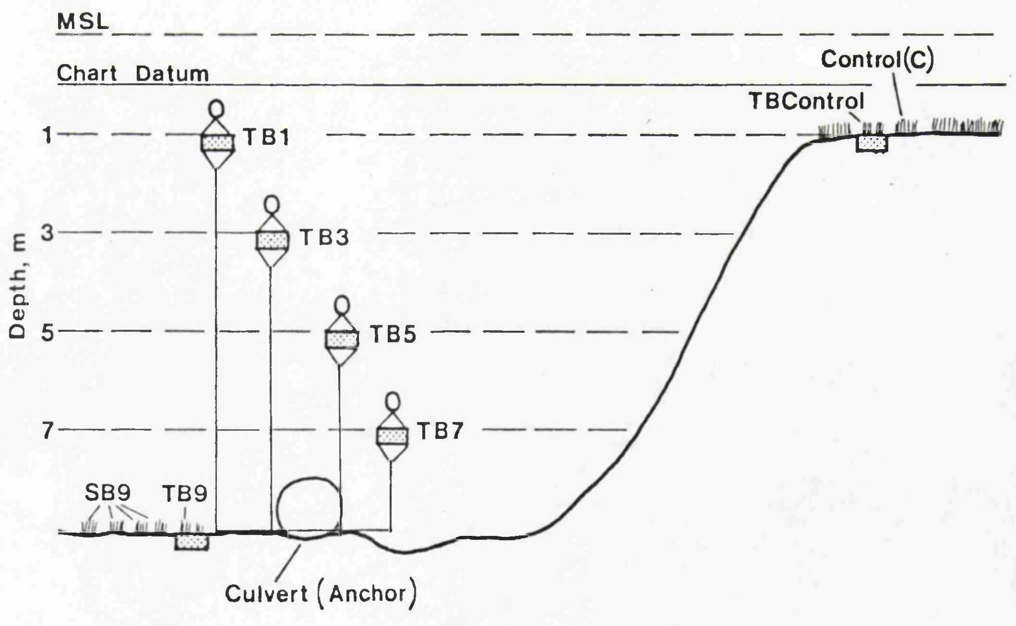


FIGURE 3.7.1.2a

i) Construction of transplant box for *Syringodium isoetifolium*.
ii) Schematic of layout of transplant boxes and transplants in dredge pit Waiqanaki III.

See also Figures 3.7.1.1a and 3.7.2.1a

TABLE 3.7.1.2a. MEAN LEAF GROWTH RATES (MLGR) FOR *SYRINGODIUM ISOETIFOLIUM* TRANSPLANTS IN DREDGE PIT WAIQANAKI III.

	Depth Below C.D. m	23-26 March 1982			30 March-2 April 1982		
		No. of Leaves	MLGR mm day^{-1}	S.D.	No. of Leaves	MLGR mm day^{-1}	S.D.
Seagrass Control, C	1	20	8.7	1.5	17	8.9	1.9
TBControl	1	9	5.9	1.6	15	6.1	1.7
TB 1	1	16	7.3	1.9	17	7.8	2.0
TB 3	3	20	8.4	1.5	8	6.5	3.5
TB 5	5	18	4.9	1.9	12	5.1	2.3
TB 7	7	24	5.9	1.6	11	4.6	1.5
TB 9	9	19	5.8	1.8	10	4.3	1.8
Sea Bed Transplants SB 9	9	17	5.4	2.0	13	5.9	1.8

TB: transplant box. For locations see Figure 3.7.1.1a and 3.7.1.2a.

For data see Appendix III.

epifaunal invertebrates and breakdown of the leaf canopy structure, thus exposing new surfaces to grazers. Schools of small foraging fish immediately congregated in the area. Either as a source of food or incidentally in pursuit of palateable epibiota, some of the seagrass leaves were grazed or broken off, frequently to the top of the sheath. This process continued long after the initial disturbance.

The immediate adverse effects of transplanting were seen clearly at the TBControl; leaves were grazed/broken and of 25 pins inserted on 23rd March, only 9 were recovered on 26th March (cf. 20 out of 25 in the seagrass bed control, C)(Appendix III).

In both experiments the highest MLGR was observed at the undisturbed seagrass control (C), 8.7 and 8.9mm day^{-1}. In the TBControl alongside, MLGR was significantly lower ($P < 0.002$ for both experiments), 5.9 and 6.1mm day^{-1}. During the first three days, MLGR in the suspended boxes was erratic; a maximum of 8.4mm day^{-1} at TB3, a minimum of 4.9mm day^{-1} at TB5.

When the leaves were re-marked on 30th March (day 7), those in TB3, TB5 and TB7 had been grazed, in the deepest box, to within 60mm of the sheath. Only those in TB1 appeared undamaged. All the leaf tips from the sea bed transplants (SB9) and TB9 were grazed/broken although leaves up to 160mm long remained. In the donor area, maximum leaf length was 320mm. During the following 3 days MLGR decreased with increasing depth from 7.8mm day^{-1} at TB1 to 4.3mm day^{-1} at TB9.

The MLGRs were compared by a 2-way analysis of variance:locations/depths by sample period. The differences between the first period (day 0-3) and the second period (day 7-10) were not significant ($P > 0.05$). However the differences between locations/depths were significant ($P < 0.02$).

By 6th April (day 14) the scheduled date for re-marking, all the leaves in TB7, TB9 and SB9 had been grazed/broken to the level of the sheath. Leaf length in TB1, TB3 and TB5 decreased with increasing depth. Leaves in the TBControl, although grazed initially, were showing signs of renewed growth. No further leaf growth measurements were made.

Immediately that the effects of grazing of the transplanted leaves became apparent, fish exclusion cages were constructed. A welded frame of 6mm diameter reinforcing rod, 300 x 300 x 300mm was covered with galvanised wire netting with a 15mm mesh diameter. On 26th March, 4 more $0.0625m^2$ turfs of *S. isoetifolium* were transplanted onto the dredge pit floor in two groups, one close to an artificial reef, the other in an open area (Fig. 3.7.1.1a)(both groups at C.D. -7.4m, MSL -8.5m). In each pair, one turf was caged. By 30th March the uncaged turfs had been grazed heavily to the level of the top of the sheath. The damage was greatest to the turf close to the artificial reef. The caged transplants remained healthy and ungrazed. Pins were inserted in 10 leaves in each cage. MLGR from 30th March - 2nd April was 6.9mm day^{-1} in both cages (Appendix III). By 2nd April, the uncaged transplants were grazed at their edges to the level of the substratum. 2 more fish exclusion cages were placed over these turfs to determine whether the seagrass would recover.

The transplant boxes and caged transplants were re-examined on 8th June, 11 weeks after transplantation. Growing leaves were found in only 2 transplant boxes, TB1 and TBControl. In both, the seagrass was flourishing, although the maximum leaf length in TB1 was only 210mm by comparison to 320mm in the control, C. In boxes TB3 and TB5 the leaves had been grazed but some sheaths remained. In TB7 and TB9 all signs of above-ground vegetation had gone, as had the transplants, SB9. The sides of the suspended transplant boxes had become covered by turf algae. These had been grazed by herbivorous fish which had also taken pieces of polystyrene, thus pock-marking the exterior surfaces of the boxes. Under the cages the turfs that had been protected since transplantation were still healthy with leaves up to 300mm long and many new leaves with intact tips. The turfs that had been open to grazing for 7 days prior to caging had shown signs of recovery: most of the sheaths had at least one leaf. Maximum leaf length was 170mm.

The identity of the grazers responsible for the damage to the transplants is uncertain. It has already been pointed out that the seagrass leaves and sheaths are heavily fouled by epibiota (algae, forams, bryozoans, hydroids, anemones, etc.) which may be more sought-after than the actual leaf. The only fish species observed amongst the transplants were the damselfish *Pomacentrus pavo*, the puffer fish *Canthigaster solandri* and the wrasse *Halichoeres trimaculatus*. However, there was, nearby amongst the artificial reefs, a reservoir of some 50+ species of fish (Section 3.7.2.2). Green turtle, *Chelonia mydas*, were observed several times (on one occasion, 3 turtles were observed simultaneously; very unusual in Fiji) around the artificial reefs and these may have played a part in grazing the *S. isoetifolium* transplants.

3.7.2. Artificial Reefs.

Once dredged or damaged by pollution an impacted area has changed environmental characteristics. These may not favour re-establishment of the original community. Restoration of productivity to these areas may be accomplished by construction of artificial reefs. On soft bottoms in particular, these provide stable substrates supporting epibenthic growth and crevices providing shelter from predators. Artificial reefs have been tailored for different requirements; restoration of dredged or polluted habitats, development of shallow and deep water fisheries, culture of shellfish, collection of aquarium fish, tourist development, etc. A wide variety of substrata have been used: concrete culverts and waste, fibreglass, recycled plastics, car bodies, tyres and sunken vessels. Large-scale reefs have been built from prefabricated parts (Chang, 1979; Sheehy, 1982; Stone, 1982), generally for the economic development of fisheries. For smaller reefs, predominantly waste materials have been used. The suitability of materials varies (Stone, 1972). Car bodies give good results but are often expensive to prepare and handle and last only 3-6 years in open ocean sites. Concrete pipes and rubble are everlasting but heavy to handle. Rubber lasts for 20 years or more and is a good substrate for attaching organisms. Stone (1979) found that the construction of artificial reefs close (< 25m) to natural reefs did not diminish the resident population of the latter. There was an increase in the carrying capacity and fish biomass in the combined area.

3.7.2.1. Construction: Waiqanaki III, September, 1980.

The highest priority in selecting substrates for artificial reefs in Fiji was to minimize costs. A diversity of materials were chosen with a requirement that each was a waste material readily available within a reasonable transport distance of the jetty. 8 car bodies, 3 concrete culverts (rejected on account of manufacturing faults), 30 cement blocks, 6 steel pipe moulds and 2 groups of 12 tyres, secured and weighted with chains, were assembled on a flat barge. The reefs were constructed at the southern end of dredge pit Waiqanaki III (Fig. 3.7.2.1a). The lay-out of the reef was less compact than intended; strong winds caused the barge to drag anchor during dumping operations.

PLATE 3.7.2.1a

Colony of *Acropora* sp. anchored on a piece of cable left by the sand dredgers in dredge pit Waiqanaki III.

In background, vehicle body A, placed in dredge pit Waiqanaki III on 16 September 1980 as part of the artificial reef construction programme (see Figure 3.7.2.1a for location of vehicle).

Photographed on 16 September 1980.

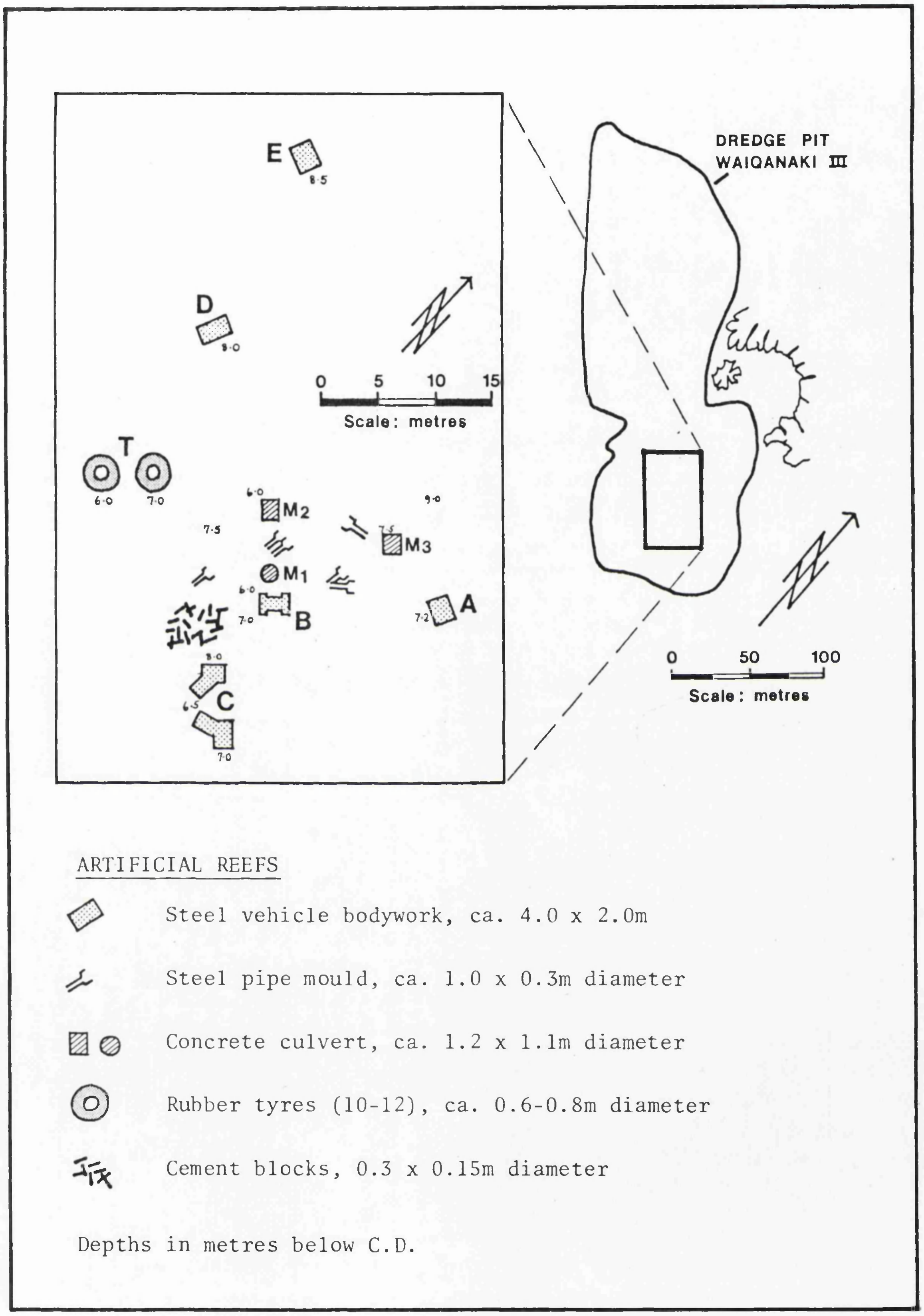


FIGURE 3.7.2.1a

Location of artificial reefs at dredge pit Waiqanaki III. Constructed 16 September 1980.
See Plate 1.1a for location of dredge pit.

3.7.2.2. Fish Colonization by April/May, 1982.

The small size of the artificial reefs facilitated the undertaking of visual census of the fish. No collections were made for identification purposes.

By April, 1982 the cement blocks had disappeared completely below the surface of the sand. Neither the steel pipes nor the concrete culverts supported a resident fish population. Fish seen grazing on these structures were resident in nearby car body or tyre reefs.

Over 900 fish representing 50 species were counted on the car body and tyre reefs (Table 3.7.2.2a). Numerically the most important group was the cardinal fish (Apogonidae), small, carnivorous, cryptic fish lying in motionless shoals inside the car bodies. The fusiliers (Caesiodinae) and damselfish (Pomacentridae) were observed in the water column above the artificial reefs. Zooplankton feeders, the former congregate in shoals, the latter, if disturbed, seek refuge in the reef. The most abundant herbivores were the surgeonfish (Acanthuridae) which graze extensively on the algal mat that covers all the substrates. The larger, more wide-ranging individuals were extremely wary of divers; their numbers were probably underestimated. These, the snappers and emperors (Lutjanidae) were the most important potential food fish. *Lutjanus kasmira* was successfully caught in traps and on lines. Less abundant but larger fish include the goatfish (Mullidae), parrotfish (Scaridae) and lionfish (Scorpaenidae). Numerous small wrasse (Labridae), blennies (Blenniidae), gobies (Gobiidae) and colourful butterfly and angelfish (Chaetodontidae) were also found around the reefs.

A possible drawback of artificial reef construction was the proliferation of the dinoflagellate *Gambierdiscus toxicus*, responsible for ciguatera poisoning in fish. Two algae samples, a *Sargassum* sp. and a section of

TABLE 3.7.2.2a. NUMBERS OF EACH FISH SPECIES RECORDED ON THE ARTIFICIAL REEFS IN DREDGE PIT WAIQANAKI III. APRIL - MAY, 1982.

FAMILY, common name / Scientific name	ARTIFICIAL REEFS: Vehicle Bodies A	B	C	D	E	Tyres T
SYNODONTIDAE, lizardfish	1		1		1	
Saurida sp.						
MURAENIDAE, moray eel						
Gymnothorax sp.	1		2		1	1
HOLOCENTRIDAE, squirrelfish						
Flammeo sammara	1		3	2		1
Myripristis sp.						1
APOGONIDAE, cardinalfish						
Apogon cyanosoma	1			40	60	3
Apogon sp. (*cf. fraenatus*)	40		3	20	4	10
Apogon aureus	50		1	20	25	1
Paramia quinquelineata	3		1	10		3
SERRANIDAE, grouper						
Anthias sp.				2		
PRIACANTHIDAE, bullseye						
Priacanthus sp.				1		
LUTJANIDAE, snapper						
S.f. LUTJANINAE						
Lutjanus fulvus		3		1	3	
Lutjanus kasmira	4	4	12	4	5	1
Lutjanus sp.					1	
S.f. CAESIODINAE, fusilier						
Caesio chrysozonus	60					
Caesio pisang				60	50	
S.f. NEMIPTERINAE, monocle-bream						
Scolopsis bilineatus	1	1				
S.f. LETHRININAE, emperor						
Gnathodentex aurolineatus			1	3		
Monotaxis grandoculis	1	8		5	14	
Lethrinus harak		1				
MULLIDAE, red-mullet, goatfish						
Mulloidichthys flavolineatus	6			3	1	
Parupeneus barberinus	1					

FAMILY, common name Scientific name	ARTIFICIAL REEFS Vehicle Bodies A	B	C	D	E	Tyres T
CHAETODONTIDAE, butterflyfish and angelfish						
Chaetodon auriga	1		2			
Chaetodon vagabundus	2		1			
Centropyge bispinosus	1		1			
Pomacanthus imperator					1	
POMACENTRIDAE, damselfish						
Chromis lepidolepis			2			
Pomacentrus pavo	14	20	15	20	60	25
Pomacentrus flavicauda	2	8	2	8		5
LABRIDAE, wrasse						
Halichoeres trimaculatus	3	10	6	5	2	12
Halichoeres sp.			1	3		
Labroides dimidiatus	2	2	1	2		3
Stethojulis sp. 1	1	1				
Stethojulis sp. 2		3				
Pseudocheilinus sp.	1		2		4	1
SCARIDAE, parrotfish						
Scarus venosus (male)					1	
Scarus venosus (female)			1			
Scarus sp.	1		2			1
CIRRHITIDAE, hawkfish						
Cirrhitichthys falco						1
BLENNIIDAE, blenny						
Meiacanthus atrodorsalis v. oualensis	2	1	1			
Aspidodontus taeniatus			2	1	1	
ACANTHURIDAE, surgeonfish						
Acanthurus xanthopterus	3				1	
Acanthurus sp. 1	1		2			
Acanthurus sp. 2					2	
Ctenochaetus strigosus	6		10	2	2	
GOBIIDAE, goby						
Acentrogobius sp.	2	10		2	3	8
Amblygobius sp.		1				
Valenciennea (Eleotriodes) sp.						1
SCORPAENIDAE, lionfish						
Pterois volitans	1		1	1	1	
CANTHIGASTERIDAE, puffer						
Canthigaster solandri	1				2	
Canthigaster valentini					1	
TETRAODONTIDAE, pufferfish						
Arothron hispidus					1	

For location see Figure 3.7.2.1a.

Authorities for generic and specific names: Appendix IV.

the algal mat from one of the vehicles, were removed to the laboratory and examined for epiphytic *G. toxicus*. None was found. Two fish from the artificial reefs, one resident, *Lutjanus kasmira*, one temporary resident, *Plectropomus leopardus*, were analysed for ciguatoxin. No toxicity was found.

3.7.2.3. Coral Colonization by April/May, 1982.

Several species of coral were found colonizing the artificial reefs. Substrate selection was clearly apparent. *Porites* sp. favoured vertical concrete surfaces on the outside of the concrete culverts. *Pocillopora damicornis* was largely restricted to angular recesses on the metal car bodies. One colony of *Plerogyra sinuosa* was found on the shady underside of a car body (area C). Corals were completely absent from horizontal and shallow sloping surfaces, both concrete and metal. Eighteen months after construction of the reefs, flat colonies of *Porites* sp. measured up to 29mm diameter. *Pocillopora damicornis* colonies 10-15mm high, 15-20mm diameter were found.

A colony of *Pocillopora damicornis* growing on a PVC stage installed in Laucala Bay in September, 1980 (Suva Reef transect line, metre 95) measured 42mm high x 30mm diameter in May, 1982.

3.8. Discussion.

The extensive subtidal, backreef, monospecific, seagrass meadows of *Syringodium isoetifolium* in Fiji have not been described from elsewhere. They are probably characteristic of a narrow transition zone lying between the Indo-Pacific region of high species richness and the impoverished Central Pacific region where only one seagrass genus, *Halophila*, is found. The seagrass genera *Cymodocea*, *Thalassodendron*, *Enhalus*, *Thalassia*, *Syringodium*, *Halodule* and *Halophila* are all characteristic of the Western-

Central Melanesia region (den Hartog, 1970). The seagrass community of Fiji lacks all four of the highly competitive flat leaved genera (first four as listed above). On account of the absence of competitors, *Syringodium isoetifolium* dominates the sublittoral community in Fiji. From the distribution maps of den Hartog (1970) it is deduced that this situation is likely to occur only in Fiji and Tonga. These island groups form the westernmost extension of the distribution of *S isoetifolium* in the absence of more competitive flat leaved genera.

Flower production in *S. isoetifolium* is seasonal. The first flowers were observed at, or soon after, the period of minimum seawater temperature (Fig. 1.3.2.1b). This is consistent with the experiments (in culture) by McMillan (1980, 1982), who induced flowering by reducing the water temperature from 27-31°C to 25-25°C (mimicking the March to August seawater temperature curve for Fiji). The duration of flowering corresponds with the period of seawater temperature increase, from September to February. The absence of staminate flowers in the research area remains unexplained. Seed production has been recorded at Thursday Island (Australia)(den Hartog, 1970) and staminate flowers have been recorded from Kenya (Issac, 1968). McMillan (1981) described seed germination of *S. filiforme*. Staminate flowers are not necessarily absent from Fiji as a whole. However, it is possible that there are no male plants in Fiji. If so, all reproduction, dispersal and recolonization must be by vegetative means. Furthermore, in the absence of sexual reproduction, the evolutionary pathway is blocked.

Flower and seed production in *Halophila minor* follows a seasonal pattern similar to *S. isoetifolium*. However the first flowers were found in June, before the seawater minimum was reached.

The extent of *S. isoetifolium* in Fiji is greatly underestimated in the literature. The distribution notes in Smith (1979) are based on intertidal and beachdrift observations. He puts *Halophila* and *Halodule* as the most abundant species in Fiji. This may be so on the accessible intertidal mudflats but does not take into account the extensive subtidal areas. In the study area *S. isoetifolium* is the least visible seagrass yet in terms of biomass is many times more important than the combined contribution of *Halophila* and *Halodule*.

There is little doubt that light energy is a prime factor in determining seagrass growth and distribution. In terms of the physiological requirements of the seagrass, light is extremely difficult to measure. Many studies have correlated total insolation, daylength and other measures of surface illumination with seagrass growth. In Fiji the summer months are characterized by longer daylength, higher daily sunshine hours, higher zenith angle and generally calmer water conditions: sea surface irradiance is increased. The converse is true for the winter months. However, the annual pattern of secchi depths shows an inverse relation to the sea surface irradiance; secchi depths are minimum (2-5m) in the summer months, maximum (5-11m) in the winter months. Secchi depth is a measure of the turbidity of the water, in turn dependent on river discharge,plankton production and local oceanographic conditions Furthermore, the seagrass meadows lie in the transitional region where the comparitively clear marine waters (MIW) meet turbid surface waters (LSW). Under such conditions, discrete measurements of surface or sea bed irradiance are largely meaningless. The problems of integral measurements of sea bed irradiance, to mimic the response of the seagrass, cannot be overestimated.

The backreef seagrass meadows are an easily accessible source of food and income for local people. Historically the fishing rights to each section of reef belonged to a particular village. This is no longer enforced in the Suva region. The reefs are fished indiscriminately and no steps are taken at management. The study area was too large to contemplate a quantitative fisheries survey (a notoriously difficult task). Even the concept of a 'before and after' survey must be taken in context. On account of the intense level of fishing, the fish population of the seagrass meadows on Suva Reef may bear no resemblance to the natural fish population of an unexploited meadow. Thus a 'before-dredging' survey is also an 'after-increasingly intensive fishing pressure' survey.

Measurement of the leaf productivity of *S. isoetifolium* is only the first stage in determination of the total productivity of the seagrass community. The leaf marking technique gives a relatively accurate measure of net leaf productivity. This is a measure of the quantity of seagrass available as a food source, directly by grazing or indirectly via detritus based food webs. However, since there is no measure of root+rhizome growth or any losses of excreted carbon compounds, net seagrass productivity is underestimated (Zieman and Wetzel, 1980). Patriquin (1973) estimated the below-ground component to be 10-13% of net seagrass productivity. The seagrass leaves are a substrate for epiphytes. Their productivity may be considerable (McRoy and McMillan, 1977; Penhale, 1977; Dawes et al., 1979) yet by shading the seagrass leaf they may reduce net leaf productivity. The total productivity of the seagrass community also includes the productivity of the loose-lying and rhizophytic algae, algal mats and phytoplankton. The contribution by each element varies with location, season and community structure. Den Hartog (1979) suggested that in a well developed community the seagrass productivity may be equalled by the combined algal productivity.

Net leaf productivity of *S. isoetifolium* was found to range from 0 to 0.62 g C $m^{-2}day^{-1}$. The overall mean net leaf productivity for the meadow (average all sites, both seasons) was 0.23 g C $m^{-2} day^{-1}$. Seawater temperature was 3°C higher during February, 1982 (28.5°C) than October, 1980 (25.5°C)(Although there are no records of sea bed irradiance, it is likely that, on average, surface irradiance and water turbidity were both higher in February, 1982 than October, 1980). There is no evidence of seasonality in net leaf productivity from this study. However, it is possible that the two experimental periods fell midway between a peak and a trough on a graph of productivity vs. time. More data are required. No values for productivity of *S. isoetifolium* are given in the literature. Zieman (In Zieman and Wetzel, 1980) measured productivity of 0.8 g C $m^{-2} day^{-1}$ in a *S. filiforme* meadow in Florida. The flat leaved seagrasses have generally higher productivity. Average values for net leaf productivity of *Thalassia testudinum* range from 1.4 to 2.7 g C $m^{-2} day^{-1}$ with upper values of 3.0 - 5.6 g C $m^{-2} day^{-1}$ (Zieman and Wetzel, 1980).

The average turnover period of *S. isoetifolium* was estimated at 54 - 55 days, i.e., 6.7 crops of seagrass leaves per year. This compares with typical average turnover periods of 54 days for *Thalassia testudinum* (Zieman, 1975) and 68 Days for *Zostera marina* (Jacobs, 1979).

From discrete leaf growth rate observations it is only possible to plot growth rate vs. <u>true</u> length for the recently emerged leaves with intact tips. From this study there is no evidence of a differential leaf growth rate between emergence and cessation of growth. Again, more data are required, ideally from serial measurements of one leaf. In other seagrasses, leaf growth pattern varies between species. Patriquin (1973) and Zieman (1975) showed that the growth rate of *Thallassia testudinum* leaves decreased exponentially with the age of the leaves. Jacobs (1979) observed a similar pattern in *Zostera marina;* leaf growth rate was maximum on emergence, decreasing with age. However, Johnstone (1979) found that the leaves of *Enhalus acoroides* grew in a linear mode; growth rate remained constant with increasing age. In *S. isoetifolium* 100% of the growth of the leaf occurs within the sheath. There is no elongation once the leaf has emerged. In this respect, it differs from *Thalassia testudinum* in which there is elongation throughout the leaf, decreasing exponentially towards the tip (Zieman and Wetzel, 1980). Where replicate biomass determinations were made, the range of values was large. The method is imprecise. The problem has been noted by several authors (see McRoy and McMillan, 1977). McMahan (1968) found that in a dense bed of *S. filiforme*, 20 above-ground biomass samples only estimated the mean by ± 30%. The problem lies in the heterogeneity of each stand of seagrass. Consider also two adjacent areas of the seagrass meadow, one colonized for 2 years, the other for 5. Both might support a comparable above-ground biomass yet, on account of greater rhizome development, the below-ground biomass of the latter would be greater. Such areas are often indistinguishable in the field.

The above-ground dry weight of *S. isoetifolium* ranged from 0 - 379 g m^{-2}. In the central section of the meadow (metre 55) mean above-ground dry weight was 202 g m^{-2}. Mean values for *S. filiforme* range from 45 g m^{-2} (McMahan, 1968) to 100 g m^{-2} (range 15 - 200 g)(Zieman, In Zieman and Wetzel, 1980).

S. isoetifolium has the capacity to infill confined disturbed areas within an established seagrass meadow. *S. filiforme* is known to be more tolerant of oxidised sediments than some other seagrass species (Patriquin, 1972). Johnstone (1975) found no evidence of *S. isoetifolium* growing in disturbed areas or where the substrate was mobile. He concluded that *S. isoetifolium* is not a pioneer species. Its absence from extensively disturbed areas in Fiji is consistent with this. *S. isoetifolium* can only be considered a pioneer species in terms of lateral extension of established beds. There is no evidence (in Fiji) of propagation by seeds or of establishment of vegetative fragments (cf. *Halophila minor*).

The seagrass transplants failed initially on account of the intense grazing pressure. The destruction of the transplants was probably accelerated on account of the fish population concentrated in the area by the artificial reefs. Grazing pressure by this introduced population may also account for the demise of the naturally colonized *S. isoetifolium* observed in dredge pit Waiqanaki III during 1980. No data are available on the longterm survival of seagrass transplants, protected by fish exclusion cages, on the dredge pit floor. However *S. isoetifolium* was never found naturally flourishing at depths greater than 5m below C.D. (Channel to SW of Toberua Island).

The pilot artificial reef construction was very modest in scale by comparison with the high technology reefs being constructed elsewhere in the world. However, for each reef development the location, reason for construction, available resources, etc. are unique.

The distribution of the fish amongst the various reef types is controlled more by the degree of shelter afforded by the habitat than the nature and texture of the substrate. Thus the intricate, dark, semi-enclosed recesses within the bodywork of the dumped vehicles is favoured over the more open environment of the concrete culverts. The groups of vehicle tyres, although well colonized by 17 fish species, provide individual habitats considerably smaller than in the vehicle bodies; this is a major factor in regulating the species composition and maximum size of resident fish.

The success of future artificial reefs could be greatly increased by careful choice of materials and some preparatory work. The arrangement of the rubber tyres would be improved by lashing them together in groups of four, creating a tetrahedral formation. Concrete structures such as the culverts with large flat surfaces are not particularly suitable either for coral settlement or as a fish habitat; a reticulated structure with many dark interstices, overhanging edges and vertical surfaces would be ideal. As fish habitats, vehicle bodywork, stripped of chassis and engine, is the most effective. It is interesting to note that the most badly damaged vehicles, providing a variety of edges, recesses and surfaces, attract the most coral settlement. Little deterioration of the car bodies was observed during the first 18 months. It is suggested that the life time of the car bodies in the protected environment of the dredge pits will be considerably longer than 3 - 6 years as observed by Stone (1972) in open ocean conditions. Other materials such as PVC pipes have been seen to be very acceptable substrates; however unless they can be obtained as a waste product it would prove very expensive on a large scale.

No evidence of fish poisoning or of the dinoflagellate responsible, *Gambierdiscus toxicus*, were found associated with the artificial reefs. Several fish species in Fiji are known to be toxic at times. The level of toxicity varies with the individual fish, location and season. Of the fish found in the seagrass beds dredge pits and artificial reefs, three species are prone to toxicity: *Gymnothorax* spp. *Sphyraena barracuda* and *Plectropomus leopardus*. A fourth species, *Ctenochaetus strigosus* was found to be toxic on Johnston Island (700km SW of Hawaii) by Brock et al. (1966).

4. Sedimentology

CHAPTER 4. SEDIMENTOLOGY.

There are several important characteristics of the backreef sediment deposits that render them ideal for cement manufacture in Fiji (K. van Vlyman, *pers. comm.*). The sediments are:-

1. pure carbonate with less than 4% magnesium carbonate;
2. accessible, uncompacted and easily won by grab-type dredgers;
3. sufficiently small-grained that they can be milled directly without costly pre-crushing.

Prior to excavation, 50-55% of the dredged area was covered by seagrass (Section 1.4.2.), the remainder comprising largely barren sand zones. There is a large literature concerning the interaction between seagrass and sediment (for review, see Burrell and Schubel, 1977). Seagrasses alter the sediment characteristics and sedimentation process in a variety of ways but the major effects are to increase the sedimentation rates, to concentrate preferentially the finer particle sizes and to stabilize the deposited sediments. Several mechanisms are responsible:-

1. entrapment of water-borne particles by the grass blades,
2. formation and retention of particles produced within the seagrass beds,
3. binding and stabilization of the substrate by root+rhizome systems.

The sedimentological aspects of this study encompass both the characteristics of the sediment and the process of sedimentation. However, since the techniques of sediment analysis are often both elaborate and time consuming and the study of sedimentation processes frequently requiring sophisticated field and laboratory equipment, the first step was to identify the issues concerning the sediment/sedimentation process that are key to the sand dredging operations. These were seen as:

1. the source of carbonate sediment;
2. the rate of accumulation (i.e., net deposition) of the backreef sediment deposits;
3. the effects of sand excavation in terms of the changes in bottom topography and rate of replenishment of sediment deposits.

4.1. The Carbonate Sediment.

The backreef sediment is predominantly biogenic in origin. It is an accumulation of the skeletal debris of calcareous organisms, the main contributory groups being corals, calcareous algae, foraminifera, echinoderms and molluscs.

To establish the source of the sediment it is necessary to have an understanding of the processes involved in reef growth (for review see Davies, 1982). The present-day reefs have been formed over the last 15,000 years during the marine transgression and sea level still-stand (Hopley, 1978; Taylor, 1978) that has followed the last major glaciation (Wisconsin). The geological structure of several Holocene reefs has been studied; most take the form of a thin carbonate "veneer" ($\leqq$ 40m thick) overlying a Pleistocene karst-eroded surface (for review see Stoddart *et al.*, 1978; also Davies and Marshall, 1979, 1980; Shinn, 1980; Marshall and Davies, 1982). The precise pattern of reef growth depends on a variety of biological, oceanographical and geological factors. Davies and Marshall (1980) demonstrated that reef growth in a transgressive, epicontinental shelf environment was first vertical, then backwards when the reef reached the sea level still-stand position. However, active seaward growth of both the reef front and reef flat has also been demonstrated (Curray *et al.*, 1970, in Micronesia). At each location the foundation, sea level fluctuations (isostatic and eustatic), oceanographic conditions (suspension loads, temperature, salinity, nutrients, tidally-induced currents, wave exposure) and reef community structure together dictate the process of reef growth. For the pusposes of this study a simplified schematic model of barrier reef formation in SE Viti Levu was drawn up (Fig. 4.1a)(after Curray et al., 1970; Hopley, 1978; Stoddart et al., 1978; Taylor, 1978; Davies and Marshall, 1980; Marshall and Davies, 1982).

Carbonate is produced to a greater or lesser degree on all areas of a living reef. On the seaward portion, production has been estimated to be in the order of 4kg $CaCO_3$ $m^{-2}y^{-1}$ (Smith and Kinsey, 1976). However, taking into account the less productive zones, Davies (1982) suggested a mean carbonate production of 1.5kg $CaCO_3$ $m^{-2}y^{-1}$ (One Tree Reef, Great Barrier Reef).

During periods of rising sea level, carbonate production is directed largely towards upward growth. However, once the reef surface reaches the still-stand sea level, net upward growth is nil: gross carbonate production on the reef crest and flat must be matched by removal of an equal amount by erosion and solution. Erosion is by a combination of physical (waves and currents) and biological (grazing, boring organisms) forces. Removal is mainly by wave and current action although some sediment may be transported by coral grazing fish (Ogden, 1977).

Carbonate formed on the fore reef slope either becomes part of the reef structure (resulting in the prograding of the reef front) or is eroded and transported downwards to the offshore deep reef slope or upwards to the reef top (Fig. 4.1b). Debris carried onto the reef flat is swept lagoonwards by shoaling waves and by the suprareefal currents (Chapter 2) along with the carbonate material produced and eroded in that region. On reaching the deeper lagoon, current velocity is generally reduced and deposition takes place, particularly in the seagrass meadows which trap

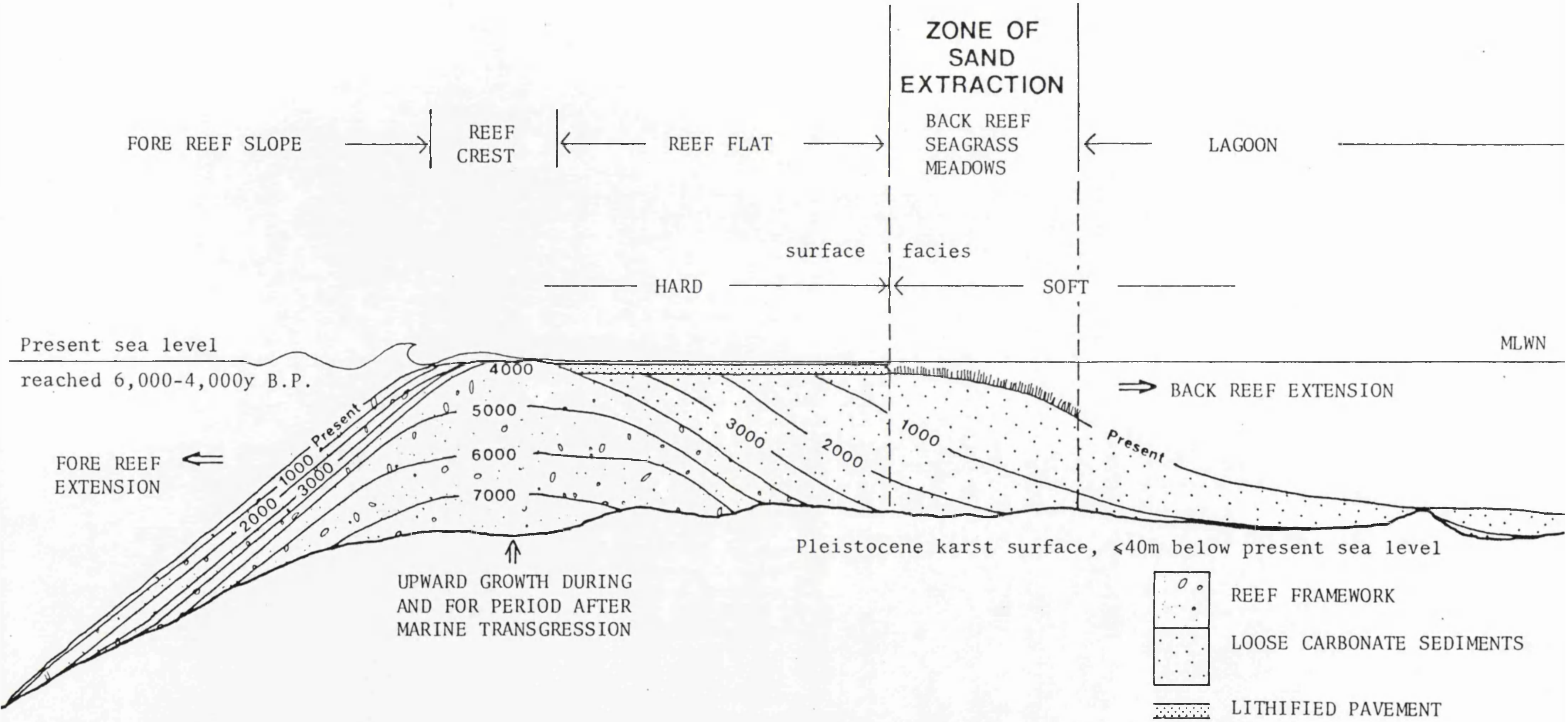


FIGURE 4.1a

Schematic cross-section of barrier reef showing possible structure and process of formation. Iso-time lines in years B.P.

After: Curray _et al._, 1970; Hopley, 1978; Stoddart _et al._, 1978; Taylor, 1978; Davies and Marshall, 1980; Marshall and Davies, 1982.

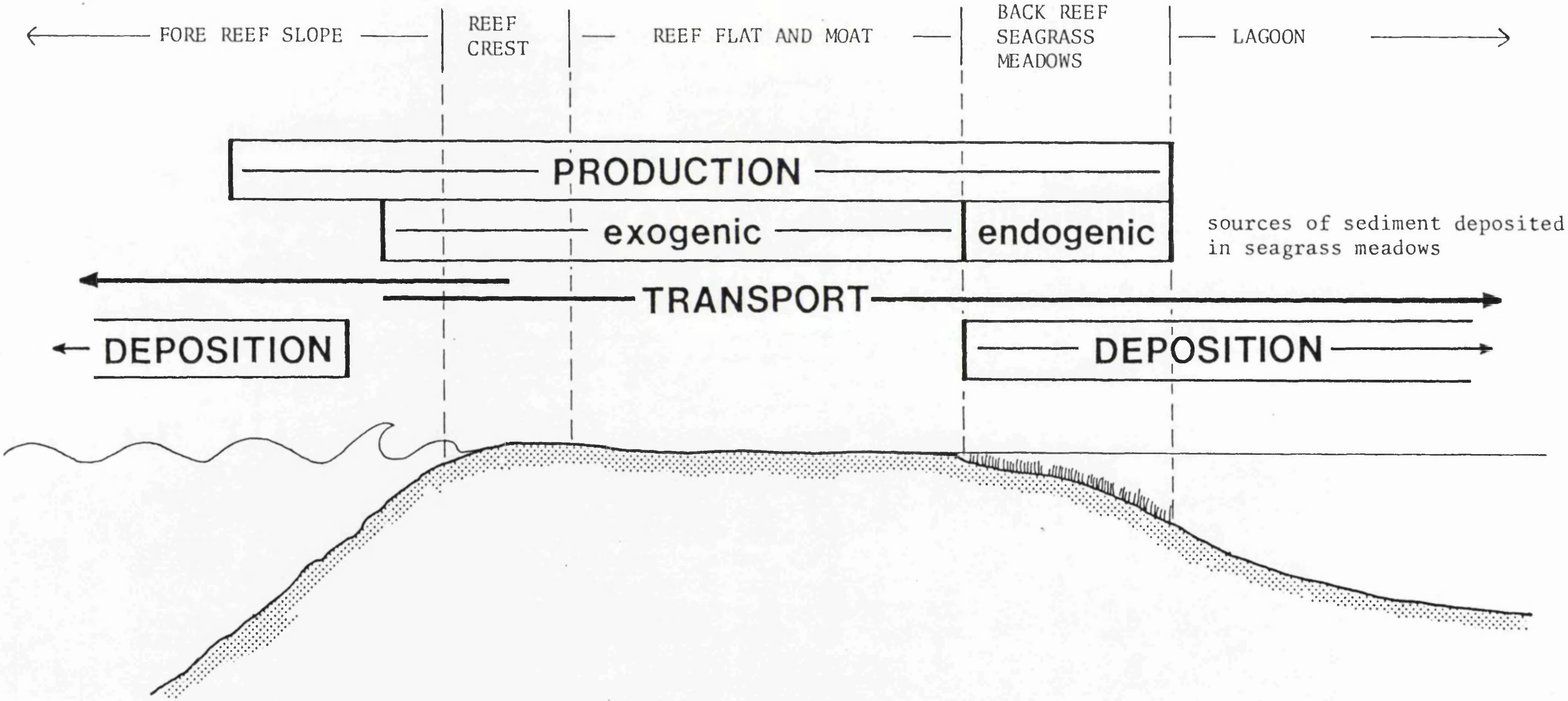


FIGURE 4.1b

Schematic cross-section of barrier reef in SE Viti Levu showing:

i major areas of sediment production
ii sources of sediment deposited in seagrass meadow
iii transport directions
iv areas of deposition

and bind the sediment. Carbonate produced in the lagoon areas is generally deposited *in situ*.

Thus there are two sources of backreef sediment (Fig. 4.1b). There is the exogenic sediment, produced on the fore reef slope, reef crest and reef flat, transported lagoonwards and deposited in the seagrass meadows and on the lagoon floor. Secondly, there is the endogenic component, produced and retained *in situ* (mainly in the seagrass meadows). The seagrass leaves provide a substrate for encrusting carbonate-secreting biota while providing a habitat and anchorage for free-living (e.g., *Galaxaura* sp.) and rhizophytic (e.g., *Halimeda macroloba*) calcareous algae, foraminifera, molluscs and echinoderms, all of which, on death, contribute carbonate skeletal debris to the sediment.

The analysis of carbonate sediments has been the subject of much contention, particularly the relative merits and interpretation of sieve techniques versus settling tube methods (for review, see Stoddart, 1978). In this study the back reef sediments were initially dry sieved, then analysed (entire size range) using a settling tube. Comparison was made between the sediments of the seagrass beds and the sediments of the open sand areas. Using sediment traps the suspension load of the suprareefal currents was also sampled. This material was analysed using the settling tube and the results were compared with those of the bottom sediments.

4.1.1. <u>Sieve Analysis.</u>

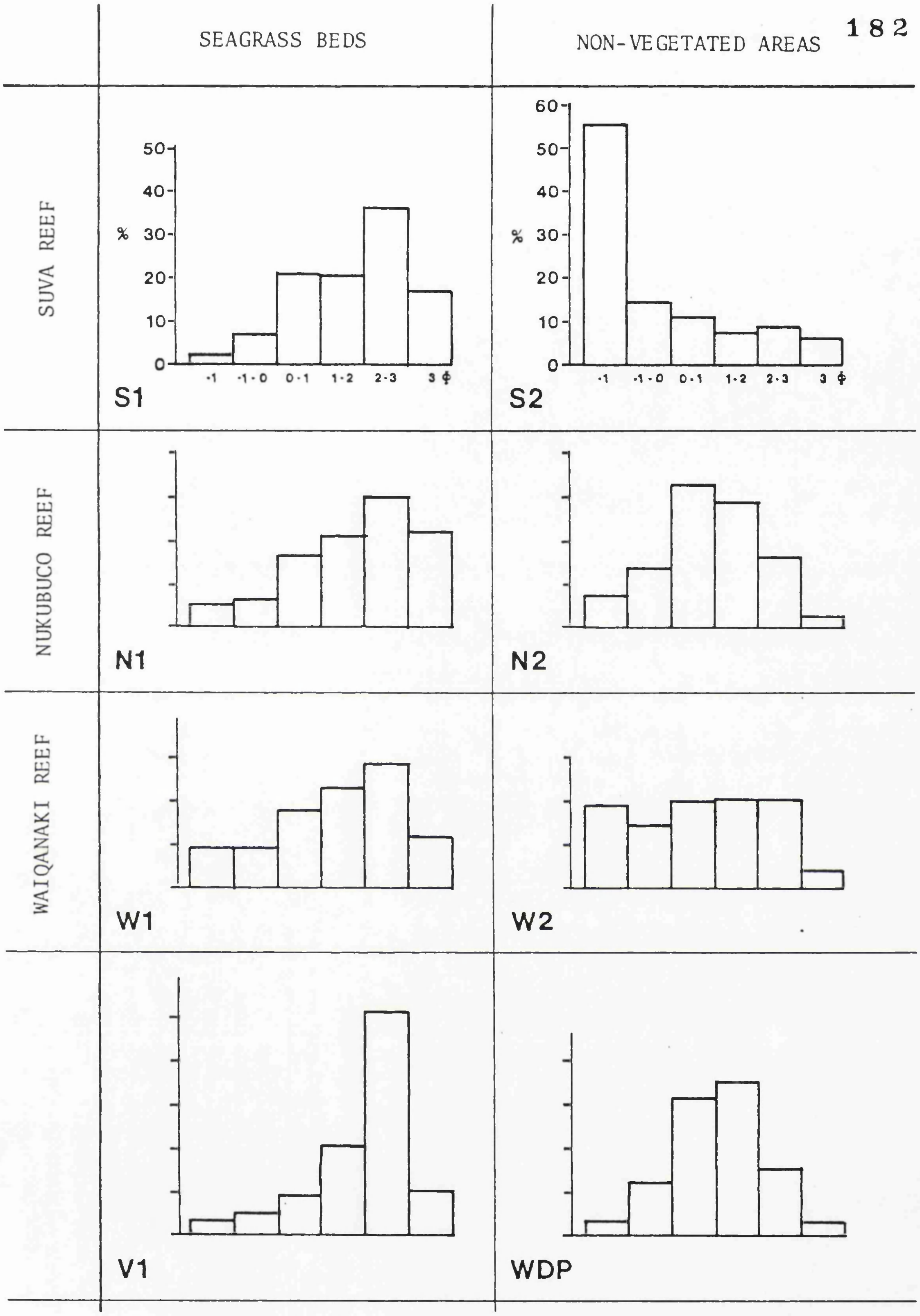
Sediment samples were collected from the seagrass meadows on Suva, Nukubuco and Waiqanaki Reefs. Samples were collected using a PVC pipe 300mm long x 80mm int. diam. fitted with a handle and stoppers top and bottom. At each location one sample was collected from an area of dense seagrass growth, a second from an adjacent (within 2m) non-vegetated area. A fourth seagrass bed sample was collected on Suva Reef, off Veiuto Point, and one sample was collected from the floor of dredge pit Waiqanaki III.

The sediments were oven dried at 105°C. Approx. 100g of each sample was then sieved for 10 minutes through a nest of 5 sieves of 1 phi intervals (-1, 0, 1, 2 and 3 phi). The results were plotted as histograms (Fig. 4.1.1a).

In all four seagrass bed sediments the modal size fraction was 125-250μm, ranging from 29% on Waiqanaki Reef to 51% on Suva Reef (off Veiuto Point). Percent fines (< 63μm) in the same samples ranged from 10 to 21%. Sediments from the non-vegetated areas were extremely heterogenous with few fines (3-6% < 63μm) and up to 55% gravel (> 2mm) fraction. The sample pairs collected within 2m of each other also showed marked heterogeneity; at all sites there was an increase in the finer fractions in the seagrass bed. On the floor of dredge pit Waiqanaki III the sediment was of an intermediate type with a modal size fraction of 250-500μm.

4.1.2. Settling Tube Analysis.

The carbonate sediments were analysed using the "sedimentation tower" described by Rigler et al. (1981). The tower was designed for the analysis of sand (2mm - 63μm) sized samples using a recommended sample split of ca. 4-5g. In this study the full grain size range of the sample including both the gravel (> 2mm) and mud (< 63μm) fractions was used in the analysis. Some workers have split the sediment sample into gravel, sand and mud fractions and then used sieving, settling tube and pipette/hydrometer techniques for the respective fractions (P.J. Davies, pers. comm.). However the separate methods yield quite different types of information (particularly with biogenic sediments) that pose serious difficulties in the re-combination and interpretation of the results.



S = Suva Reef transect line C.D. - 2m

N = Nukubuco Reef, by dredge pit II C.D. - 1m

W = Waiqanaki Reef, by Waiqanaki III C.D. - 1m

V = Suva Reef, off Veiuto Point C.D. - 1m

WDP = Waiqanaki III, dredge pit floor C.D. - 9m

1 = from seagrass beds (*Syringodium isoetifolium*)

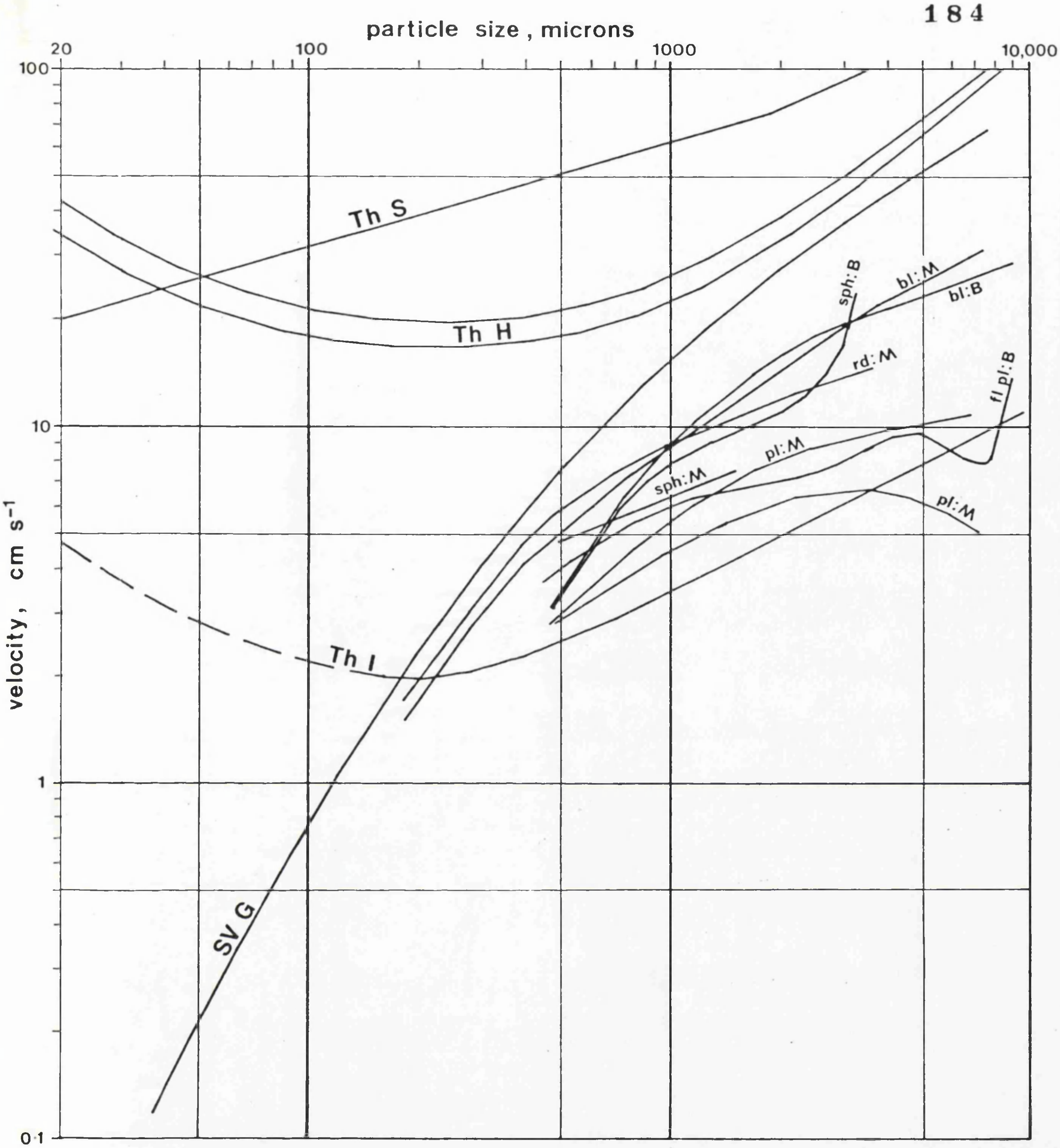
2 = from non-vegetated sand area

FIGURE 4.1.1a

Grain-size distribution of carbonate sediments from seagrass beds, non-vegetated sand areas and dredge pit floor.

The maximum possible duration of the settling tube analysis (instrumentational limitation; see Rigler et al., 1981) was 307 seconds and the initial height of the water column was 185cm. Thus the instrument had the capacity to record particles with settling velocities ≧ 0.60cm s^{-1}. For the analysis of the suspension load sediments the weighing pan was raised, reducing the height of the water column to 92cm, thereby increasing the sensitivity of the apparatus to particles with settling velocities ≧ 0.30cm s^{-1}.

As a rough guide, experimental work by Gibbs et al. (1971) demonstrated that the settling velocity (in fresh water at 20°C) of individual glass spheres of 63μm diam. was 0.33cm s^{-1}. A settling velocity of 60cm s^{-1} corresponded to a sphere diam. of 85μm, 0.30cm s^{-1} to a diam. of 0.60μm. Since analyses in this study were conducted using multi-grain samples of carbonate material of a wide range of size fractions, no absolute comparison can be made with the above figures. However, the settling velocity of biogenic carbonate material is generally less than that of quartz density material (Maiklem, 1968; Braithwaite, 1973; Komar, 1981; cf. Gibbs et al., 1971; see Fig. 4.1.2a) and it is probable that in the settling tube experiments in this study, the mud fraction (< 63μm) was largely excluded from the analysis (but not entirely so, on account of the interaction between settling grains, the coarser grains "drawing" some of the finer grains downwards in their wake). This has bearing on the interpretation of the cumulative percent settling velocity curves (Fig. 4.1.2b): for samples containing a significant percentage of fines (< 63um)(e.g., the seagrass bed samples, particularly N1 and S1, Fig. 4.1.1a) the origin should be displaced up the y-axis, the amount depending on the percentage of material not reaching the weighing pan during the measurement period. However, there are no experimental data (i.e., calibration) on which to



Threshold velocity curves; quartz density material:

Th S : Sundborg (1956); in Miller et al. (1977).
Th H : Hjulstrom (1935)
Th I : Inman (1949)

Settling velocity curve; quartz density material:

SV G : Gibbs et al. (1971).

Settling velocity curves; bioclastic material:

bl:M : blocks; Maiklem (1968)
rd:M : rods; Maiklem (1968)
sph:M : spheres; Maiklem (1968)
pl:M : plates (2 types); Maiklem (1968)
sph:B : spheres; Braithwaite (1973)
fl pl:B : flat plates; Braithwaite (1973)
bl:B : blocks; Braithwaite (1973)

FIGURE 4.1.2a

Settling and threshold velocities of quartz density spheres and bioclastic grains of various shapes.

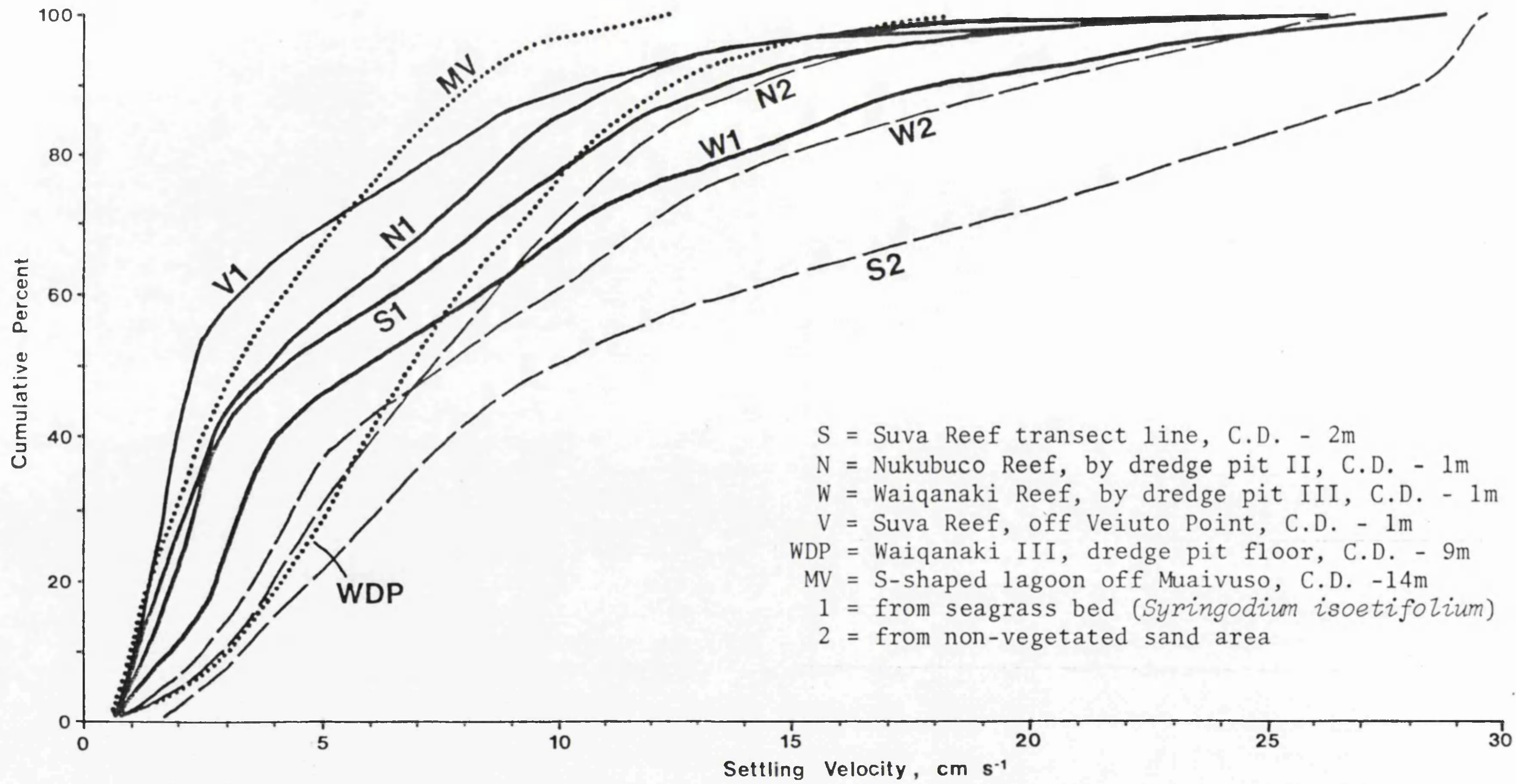


FIGURE 4.1.2b

Cumulative percent settling velocity curves for carbonate sediments. For sample locations see Plates 1.1a and 1.1b and Figures 1.1b and 2.1a decide the "cut-off" points, i.e., the grain size at which the settling velocity equals 0.60 or 0.30cm s^{-1}, for these carbonate sediments. Thus, since in some samples, the analysis fails to record fully the finest fractions, no statistics (mean, s.d., etc.) were derived from the curves.

The results of the settling tube analyses are shown in Figure 4.1.2b. The samples were the same as those analysed by sieving (Section 4.1.1.) with one additional sample from the floor of the S-shaped lagoon off Muaivuso village (Plate 1.1a and Fig. 1.1b).

The cumulative percent settling velocity curves of the seagrass bed sediments (N1, S1, W1, V1) take the form of a double-sigmoidal curve (Fig. 4.1.2d), each section of the curve with a point of maximum gradient, indicative of a settling velocity mode. The first mode (Mode 1) is at ca. 2-3cm s^{-1}, the second (Mode 2) at ca. 9cm s^{-1} (this pattern would be maintained regardless of the error induced by non-measurement of the finest fraction). The curves of the non-vegetated sediments are more variable. W2 has the features of the seagrass bed sediments although the curve is displaced to the right along the x-axis. N2 has a more classic "uni-modal" sigmoidal curve closely resembling that of the sediment from the floor of dredge pit Waiqanaki III (WDP). The point of maximum gradient on these curves occurs at a settling velocity similar to the mode of the uppermost curve for the seagrass bed sediments (Mode 2, Fig. 4.1.2d). Sediment S2 is exceptional on account of the inclusion of coarser material with rapid settling velocities, thus depressing the upper section of the curve.

Material settling out of suspension in the seagrass meadow was collected in sediment traps (Section 4.2.1.). For the purposes of this analysis the contents of several adjacent traps were combined to make up a sample weight of ca. 4-5g. The spread of the cumulative percent settling velocity curves (Fig. 4.1.2c) showed no clear relation to the

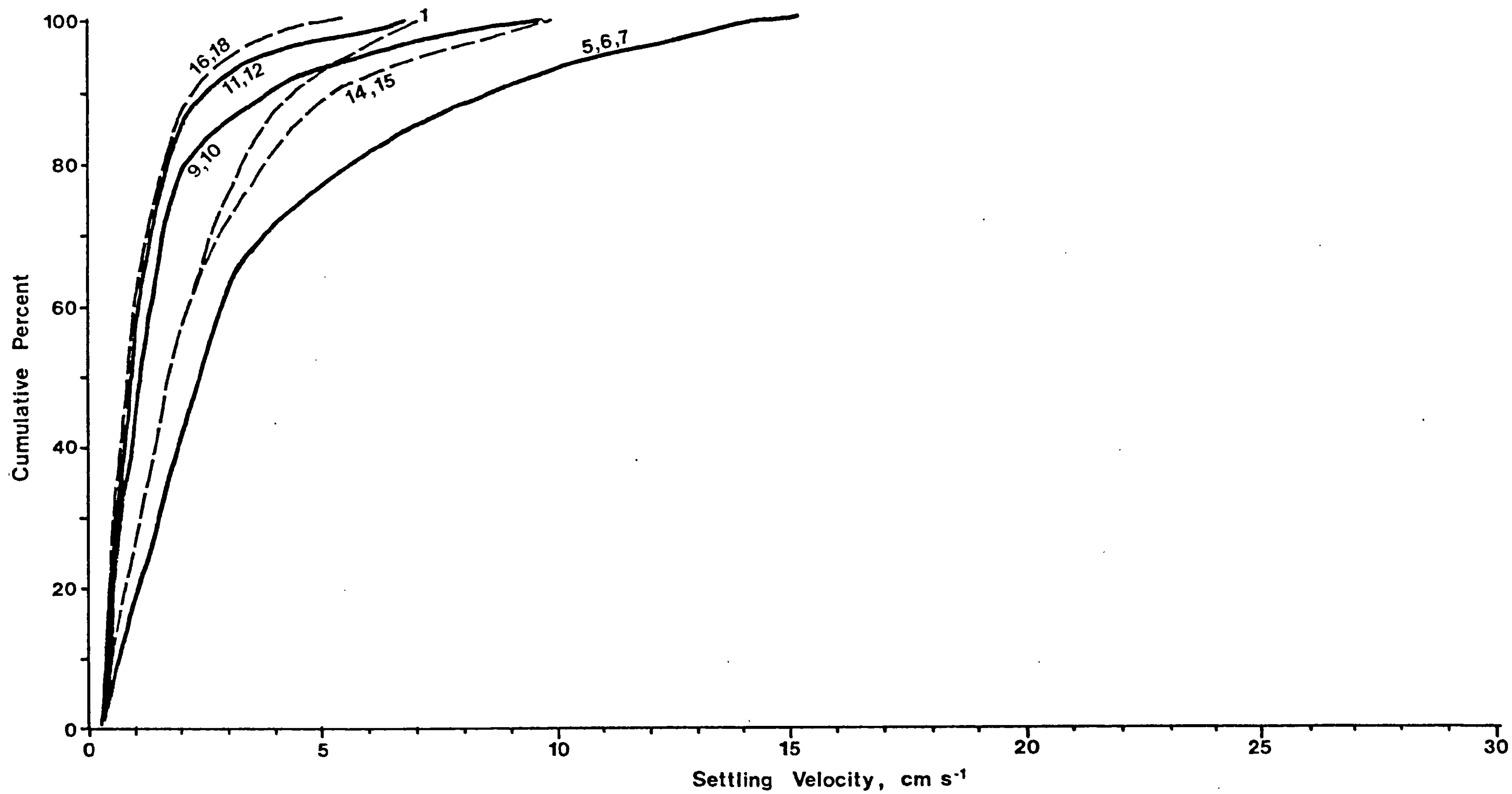


FIGURE 4.1.2c

Cumulative percent settling velocity curves for sediments collected in sediment traps along the Suva Reef transect line. See Section 4.2.1 and Figure 4.2.1a for locations of sediment traps (Nos. 1-18), Figure 2.1a for location of Suva Reef transect line.

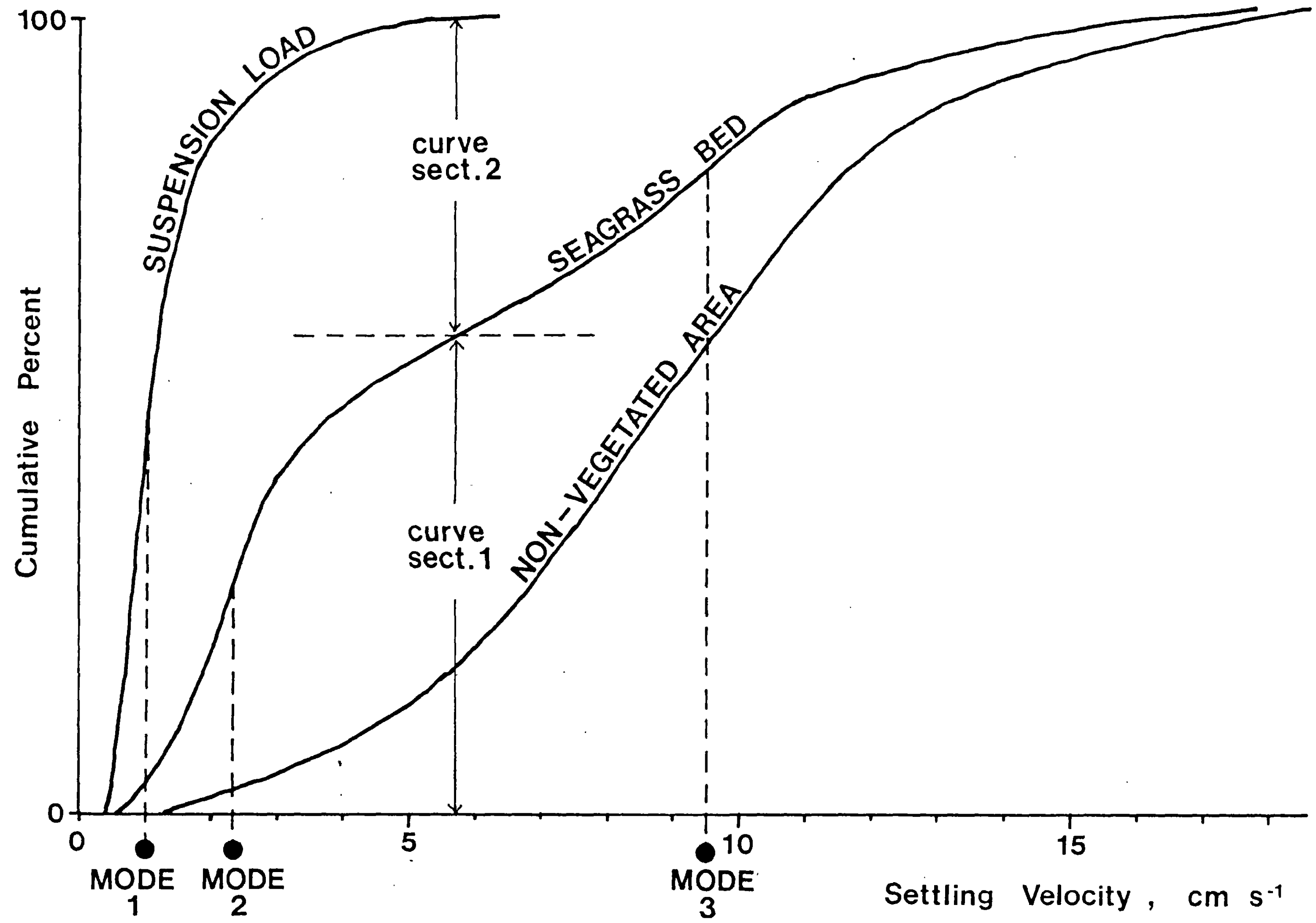


FIGURE 4.1.2d

Schematic comparison of cumulative percent settling velocity curves of sediments from:

i) seagrass bed ii) non-vegetated sand area (adjacent to i) iii) suspension load above seagrass meadow position of the traps along the transect line. The possibility of inclusion of sediments disturbed by bioturbation cannot be discounted (see Section 4.2.2). The modal settling velocity of the sediments (Mode 3) was < 2cm s^{-1} (Fig. 4.1.2d).

4.2. The Rate of Accumulation of the Backreef Sediment Deposits.

The methods for estimating rate of sediment deposition can be categorized under either supply or stratigraphic methods (Sverdrup *et al.*, 1942). The supply method is based on a computation of the total quantity of sediment supplied by the probable area in which deposition occurs. This requires detailed knowledge of the reef community structure, the rate of gross carbonate production by each community element and the mechanisms of erosion, transport and net deposition. This approach was not considered in this study.

Stratigraphic methods consider the deposition of sediment only in the immediate area of interest. Three approaches were adopted in this study. In the first, sediment traps (Section 4.2.1) were used to obtain a measure of *gross* deposition, largely from the suspension load. There were many drawbacks to this technique:

1. The efficiency of the sediment traps in sampling the suspension load was unknown. Furthermore saltation and traction loads were probably underestimated, if sampled at all.
2. The traps collected exogenic sediments but not endogenic sediments (see Fig. 4.1b).
3. The experimental time period was too short to be representative of the overall depositional processes. From these experiments a measure was obtained of the suspension load under prevailing conditions. No account was made for the effects of episodic, catastrophic, events (cyclones, earthquakes, tsunami) which may

far outweigh the effects of day to day processes. The nature of these events may be either erosional (re-suspension of sediments deposited under prevailing conditions) or depositional.

The second approach was to install stakes in the sediment deposits as reference markers against which to monitor net sediment deposition (i.e., sediment accumulation)(Section 4.2.2).

The third approach was to investigate the geological structure of the backreef deposits. The subtidal sediment deposits were investigated by seismic profiling. However, on account of the shallow water depths (1-10m) and heterogenous sediments (including coral rubble) this technique did not yield any useful results; distortion and attenuation of the signals completely masked any subsurface features. The intertidal areas were investigated by drilling a series of boreholes (Section 4.2.3). Eight of the core samples were dated using radiocarbon analysis.

4.2.1. Sediment Traps.

A detailed laboratory and field evaluation of sediment traps was carried out by Gardner (1980a, 1980b). The process of particle trapping is complex. On account of differences in geometry, boundary layer structure, turbulence and roughness scales a sediment trap does not approximate the sea floor in the manner in which particles are collected. A trap is required that collects particles at a rate equivalent to the downward flux of sediment. Gardner pointed out that a trap could yield the correct vertical flux value either by collecting those particles responsible for the vertical flux at that point, or by collecting a mass of particles equivalent to the vertical flux for the area of the trap. He concluded (Gardner, 1980b) that the downward flux (in flows up to 0.15m s^{-1}) is most accurately yielded by a cylinder with a height:width ratio between 2 and 3.

The sediment traps used in this experiment were straight-sided, cylindrical, glass jars, 180mm high, with an aperture diameter of 64mm (H:W ratio = 2.8) and fitted with plastic screw-top lids. On account of the continual bioturbation within the seagrass meadows the sediment traps required a substantial immoveable base. Concrete blocks were cast, 310 x 310mm length x width and 200mm deep with a recess to take the sediment trap. The blocks were dug into the sediment, using an air-lift suction pump, until the top surface of the block was flush with the sea bed. They were installed at 10m intervals along the length of the transect line. In order to test the reproducibility of the sediment traps, two blocks were placed side by side at the top and bottom ends of the line (metres 0 and 150). Since the sediment surface was never completely flat there were invariably areas of the block slightly higher or lower (± 15mm) than the surrounding sediments; this led to sediment being swept across the surface of the blocks. To prevent this entering the trap, when fully inserted in the block the trap aperture remained 50mm above the concrete surface. The jars, cleaned and filled with water in the laboratory, were installed in the blocks with the lids in place. Working down current a slightly underweighted diver then removed the lids. After 7 days the lids were replaced,working up current, and the jars removed to the laboratory. The contents of the jars were filtered through preweighed glass fibre filters and the dry weight (105°C) of the sediment was determined.

Two sediment trap experiments were carried out, the first (SED 1) from 20 to 27 May 1980, the second (SED 2) from 29 August to 5 September, 1980. The results (Table 4.2.1a) were expressed as rates of sediment deposition (weight) at each location in units of kg $m^{-2}y^{-1}$. Using an *in situ* density value for the carbonate sand of 1.22 tonnes m^{-3} (Section

TABLE 4.2.1a. WEIGHT OF SEDIMENT COLLECTED IN TRAPS ALONG SUVA REEF TRANSECT LINE.

Sediment Trap No.	Transect Line Location (m)	Weight of Sediment Trapped kg m^{-2} y^{-1}	
		Sed. Expt. 1	Sed. Expt. 2
1	0	26.7	54.9
2		20.2	40.1
3	10	85.8	34.6
4	20	29.5	36.4
5	30	20.5	59.4
6	40	73.4	35.5
7	50	30.5	17.7
8	60	19.8	23.1
9	70	27.2	25.0
10	80	41.9	19.3
11	90	33.8	10.6
12	100	27.4	20.1
13	110	19.5	43.2
14	120	22.9	52.2
15	130	25.9	62.9
16	140	15.2	15.7
17	150	13.5	20.6
18		15.5	15.9
Mean		30.5	32.6
Standard Deviation		19.3	16.5

Expressed in units of kg m^{-2} y^{-1}.

To convert to mm y^{-1}, multiply by 0.82.

SED Expt 1: 20-27 May, 1980. SED Expt 2: 29 Aug - 5 Sept, 1980.

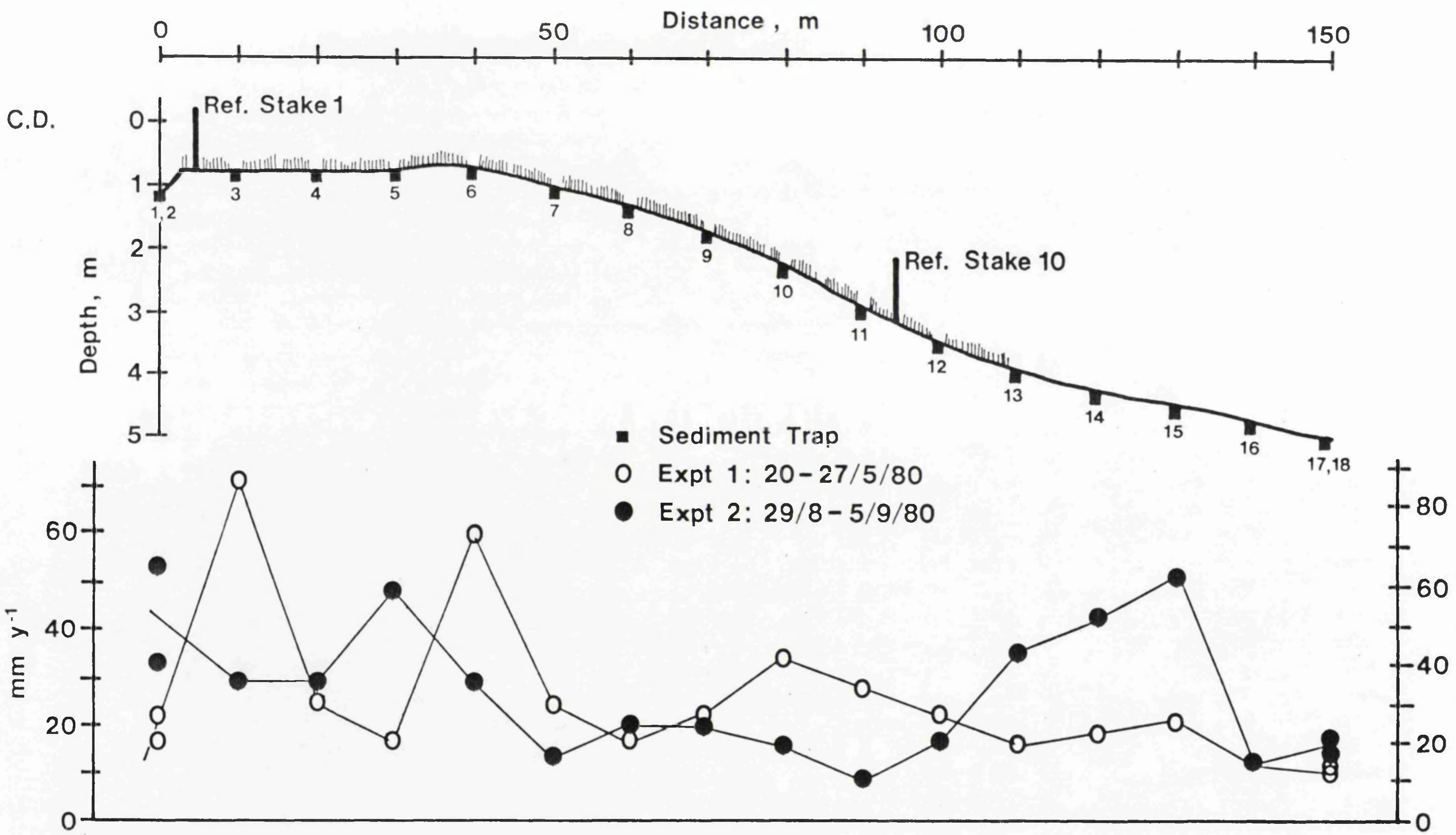


FIGURE 4.2.1a

Profile of Suva Reef transect line showing locations of sediment traps and results of experiments SED 1 (20 - 27/5/80) and SED 2 (29/8 - 5/9/80).

1.4.2) the results were also calibrated in units of vertical accretion, mm y^{-1} (Fig. 4.2.1a).

The sediment deposition rates showed no obvious correlation with position along the transect line, water depth or presence/absence of seagrass (Fig. 4.2.1a). The range of values was large, 10.6 to 85.8kg $m^{-2}y^{-1}$. The mean (± 1 s.d.) values were 30.5 ± 19.3 and 32.6 ± 16.5kg $m^{-2}y^{-1}$ for experiments SED 1 and SED 2 respectively. Field observations at the time of collection of the sediment traps indicate that the high values of traps 3 and 6 in experiment SED 1 were partially due to the effects of bioturbation. If these two results are excluded from the analysis, then the mean deposition rate was 24.4 ± 7.5kg $m^{-2}y^{-1}$ (SED 1). This is equivalent to a vertical increment of 20mm y^{-1} (20m $1000y^{-1}$). For SED 2, the vertical increment was 27mm y^{-1} (27m $1000y^{-1}$).

4.2.2. Reference Stakes to Monitor Sediment Accumulation.

PVC pipes (i.e., reference stakes) were driven into the sediment at 5 locations. The dimensions of the pipes and method of installation is shown in Fig. 4.2.2a. Note that it was essential to drill several small holes through the wall of the pipe to allow trapped water to escape as the pipe was hammered in.

Two stakes were installed at the bottom of the Nukubuco dredge pit (area II,pits A and B, see Section 4.3.) and 2 along the Suva Reef transect line (Fig. 4.2.1a). The fifth stake (V) was installed in the floor of the enclosed S-shaped lagoon off Muaivuso Village (see Plate 1.1a and Fig. 1.1b). This stake was driven into the fine sandy bottom (sediment MV, Fig. 4.1.2b) at 14m below C.D. in an area of crustacean mounds ca. 0.3m from trough to peak.

16-20 months later the stakes were remeasured and sediment accumulation (net deposition) was calculated (Table 4.2.2a). At Stake 1 there had been a reduction in sediment thickness of 60mm. Between

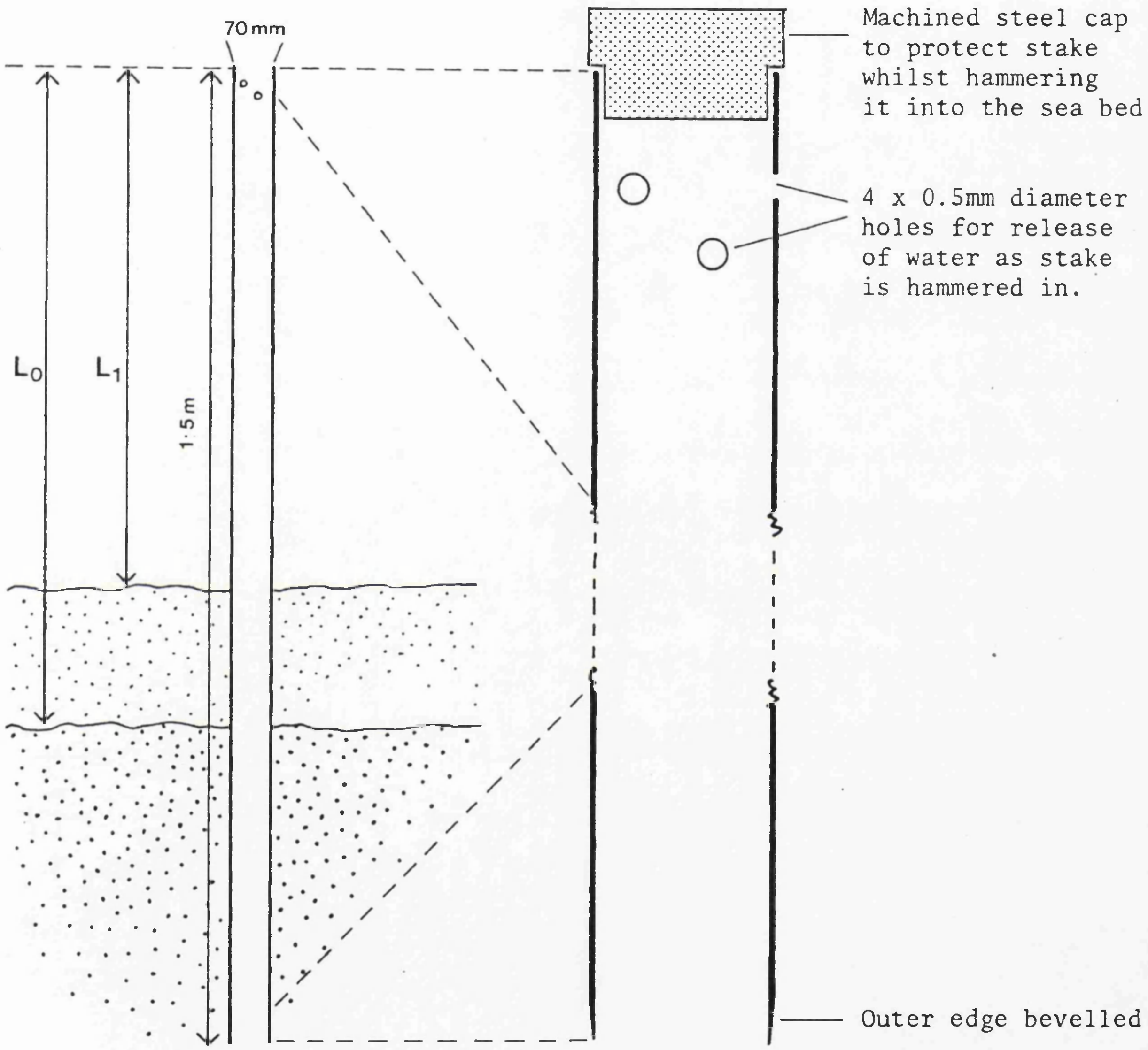


FIGURE 4.2.2a

PVC reference stake used to monitor sediment accumulation (L_0 - L_1)

TABLE 4.2.2a. SEDIMENT ACCUMULATION (NET DEPOSITION) AT REFERENCE STAKES.

Stake Code	Location	Date Installed	Date Remeasured	Time Interval Months	Net Deposition mm
1	Suva Reef transect line metre 5	30/10/80	23/02/82	16	- 60
10	Suva Reef transect line metre 95	30/10/80	23/02/82	16	+ 20
IV	Nukubuco Dredge Pit A	28/09/80	23/02/82	17	+225
II	Nukubuco Dredge Pit B	28/09/80	23/02/82	17	+435
V	Enclosed lagoon off Muaivuso	08/09/80	11/05/82	20	- 10

installation and re-measurement there had been erosion of the seagrass bed in this region leaving a non-vegetated area of sand. At Stake 10, the downstream, deeper, seagrass zone, there was a sediment accumulation of 20mm over 16 months. At Stakes IV and II, sediment accumulation was 225 and 435mm respectively: these results are discussed in Section 4.3. Stake V, in the lagoon off Muaivuso Village recorded a 10mm reduction in sediment thickness. Measurement in this area was severely complicated by the ever changing pattern of crustacean mounds.

4.2.3. Boreholes and Radiocarbon Dates.

The reef drilling was carried out in conjunction with the Mineral Resources Department (Overseas)(Fiji Government) who provided all the drilling equipment and personnel. The drilling programme had two objectives:

(a) To assess Mineral Resources Department capacity for reef drilling (an offshore drilling programme had not previously been attempted).

(b) To investigate the reef structure in relation to coral sand resources in concession areas leased and applied for by Fiji Industries Ltd.

Project objective (b) was initiated by the author and it was on the compatible basis of (a) and (b) that the drilling programme was completed. Full details of the drilling equipment, procedures and limitations, the geologist's log and full core descriptions were given by Holmes (1980).

The holes were drilled using a Mindrill Miner Mk. 3 Diamond Drill, a hand-held petrol-driven drill, using a 1-5/8" int. diam. (2-1/4" ext. diam.) drill bit, an 18" core barrel and 1-5/8" ext. diam. drill rods. The main problem encountered during operation was the entrapment of the broader core barrel at the bottom of the hole by material caving in onto the narrower drill rods. Since no casing was available and unconsolidated material was encountered at all locations, the effective drilling depth (without risking loss of the entire drill string) was limited to ca. 7m (23ft).

The problems associated with the drilling of reef framework and sediments, typically varying from soft to very hard with interspersed cavities, has been noted by most who have attempted to do so (e.g., Thom et al., 1978; D. Hopley, pers. comm.; J.F. Marshall, pers. comm.). In this series of boreholes, recovery was variable, from very low (maximum 8%) to none at all: these values are not atypical of comparative studies.

Three boreholes were drilled, two on Nukubuco Reef and one on Namuka Reef (Fig. 4.3.2a).

Borehole A. (MRD(O) ref: M/ENG/45/80 - A), 24/9/80, Nukubuco Reef.

This drill site was situated on a typical reef flat area of unbroken lithified, reef pavement. The drill met resistance for the first 0.2m and then penetrated to a depth of 7m with very little further resistance to drilling. At no stage was there resitance equivalent to that of the reef surface. No coral blocks were encountered and no core was retrieved. A 1m diam. section of the pavement was lifted up using the drill and crow bars. The pavement comprised an open structure of well cemented *Acropora* fragments generally 15-18mm diam. and 90-160mm in length. The underside of the pavement was stained a deep red/brown colour. Below the pavement was a poorly sorted carbonate sediment incorporating many coral sticks in a sand/mud matrix. Using a water jet this sediment was easily penetrated to at least 0.6m (arm's length).

Borehole B. (MRD(O) ref: M/ENG/45/80 - B), 25/9/80, Nukubuco Reef.

This borehole was run down to 7m from a site in a shallow (0.3m) moat on the reef top, seawards of Borehole A. Resistance to drilling was slightly greater than at Borehole A but cores were only recovered from 3

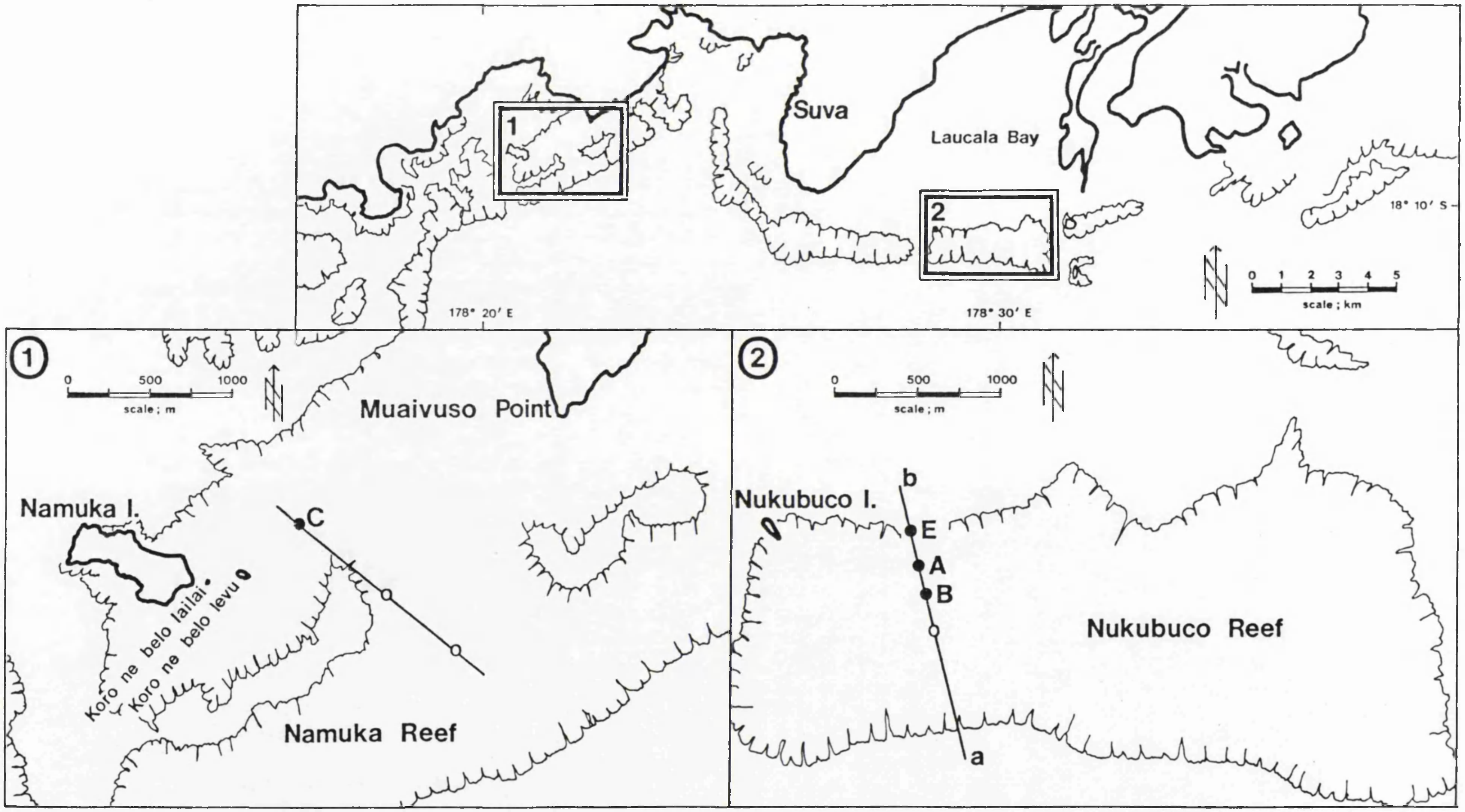


FIGURE 4.2.3a

Borehole locations on Nukubuco and Namuka Reefs

A,B,C = borehole locations
E = location of coral block (*Diploastrea heliopora*), exposed by dredging
a——b = reef cross-section illustrated in Figure 4.2.3b
O = proposed borehole sites; not drilled

levels: 0.3m (reef pavement), 2·6m and 6.1m (overall 2.5% recovery). The core sections retained at 2.6 and 6.1m were both from small *Porites* colonies (10-20cm diam.). The drilling characteristics of the large intervals of non-recovery were not greatly dissimilar to those of Borehole A (drill operator's observations).

Borehole C. (MRD(O) ref: M/ENG/45/80 - C), 26/9/80, Namuka Reef.

This drill site was situated on the "intermediate" reef area lying between Muaivuso Point and Namuka Island, within the lease area applied for by Fiji Industries Ltd. (Fig. 1.4.2b). Penetration to a depth of 7m (end of hole) was very variable with overall recovery of 8%. Small coral colonies ≦ 20cm thick were cored at depths of 3.3, 4.0 and 5.8m. All were probably of the genus *Pavona*. A sample of *Acropora* fragments was recovered from 0.6m.

The ages of 8 of the core sections were determined by radiocarbon analysis at the N.E.R.C. Radiocarbon Laboratory (Table 4.2.3a). One further coral sample (E) was collected for radiocarbon dating. This was chipped from a colony of *Diploastrea heliopora* lifted from a depth of 4.6m below the sea bed during sand dredging operations (for location see Fig. 4.2.3a).

The borehole locations and radiocarbon ages are shown on a cross-section of Nukubuco Reef (Fig. 4.2.3b; see Fig. 4.2.3a for orientation of section). Most reef dating studies have been concerned with the vertical accretion of the reef framework. Rates of vertical accretion (in units of m $1000y^{-1}$) are usually calculated as:

$$\frac{\text{depth of colony A} - \text{depth of colony B (m)}}{\text{age of colony A} - \text{age of colony B (y B.P.)}} \times 1000$$

Calculated in this way, rates of vertical accretion in Borehole B range from 1.6 to 5.3m $1000y^{-1}$ (mean 3.2 ± 1.9m $1000y^{-1}$) and in Borehole C, from 1.1 to 4.9m $1000y^{-1}$ (mean 2.4 ± 1.5m $1000y^{-1}$).

TABLE 4.2.3a. RADIOCARBON DATING RESULTS FROM CORED CORALS ON NUKUBUCO (A, B, E) AND NAMUKA (C) REEFS.

Borehole Code	Sample Composition[a]	^{14}C lab[b] Code and Number	Depth Below Sea Bed (m)	C-14 age years B.P.[c] ± 1σ
A	*Acropora* sp.	SRR-1960	0.1	4350 ± 50
B	?	SRR-1961	0.3	4970 ± 60
B	*Porites* sp.	SRR-1962	2.6	6370 ± 60
B	*Porites* sp.	SRR-1963	6.1	7030 ± 50
C	*Acropora* sp.	SRR-1964	0.6	3400 ± 50
C	*Pavona* sp.	SRR-1965	3.3	4960 ± 50
C	*Pavona* sp.	SRR-1966	4.0	5580 ± 50
C	*Pavona* sp.	SRR-1967	5.8	5470 ± 50
E	*Diploastrea heliopora*	Beta-1845	4.6	1770 ± 80

[a] Samples examined and commented upon by Associate Professor M. Pichon, James Cook University of North Queensland.

[b] SRR = Scottish Universities Research and Reactor Centre (N.E.R.C. Radiocarbon Laboratory).

Beta = Beta Analytic Inc., Radiocarbon Laboratory.

[c] B.P.= years before 1950 A.D.

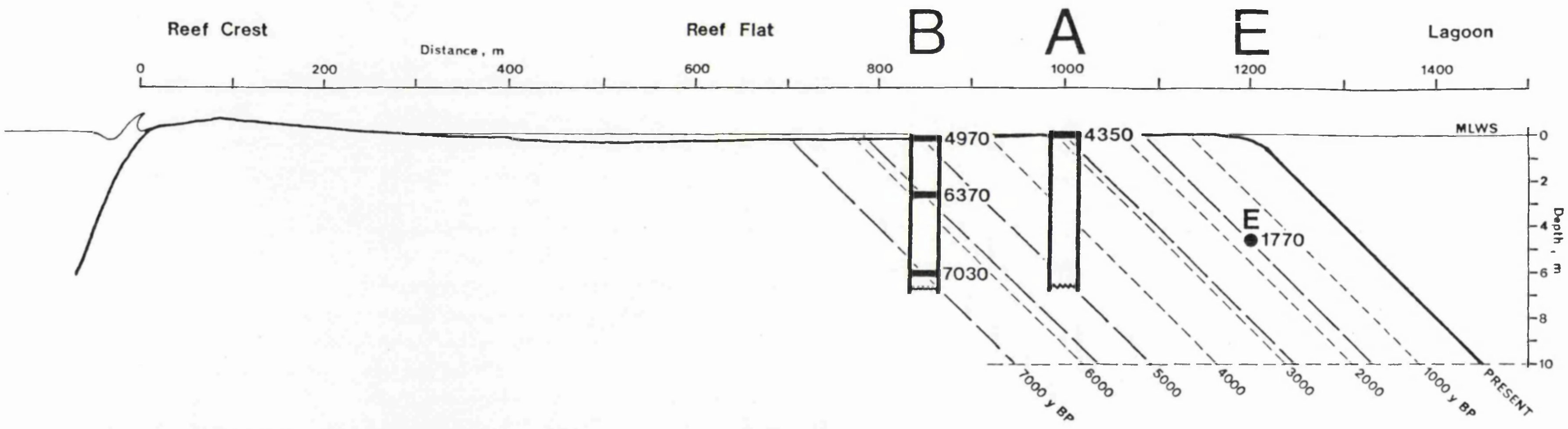


FIGURE 4.2.3b

Cross-section of Nukubuco Reef showing borehole locations, radiocarbon dates (y B.P.) and inferred iso-time lines (y B.P.).

For location of cross-section see Figure 4.2.3a

However, the process of backreef sediment accumulation has both *vertical* and *lateral* components. With reference to the schematic for barrier reef formation proposed in Section 4.1. (Fig. 4.1a) a mathematical model was used to calculate sediment accumulation rates. The schematic was simplified (Fig. 4.2.3c) and for the purposes of the model it was assumed that the back reef sediments accumulate (and have accumulated in the past) evenly down the lagoon slope; i.e., the slope of the surface of the deposits has remained constant during the past 7,000 years or more.

The following values were assigned to the model:

$s = 10m$. In the absence of seismic data or deeper (> 7m) borehole data, the only indication of the vertical thickness of the sediment deposits (s) is that the dredge pits have regularly been dug to a depth of 10m below the sea bed without observing any discontinuity (i.e., $s \geqq 10m$).

$\theta = 2.3°$. The angle of lagoon slope (θ) at the Suva Reef transect line is 2.3° (Fig. 4.2.1a; metre 50 to 150).

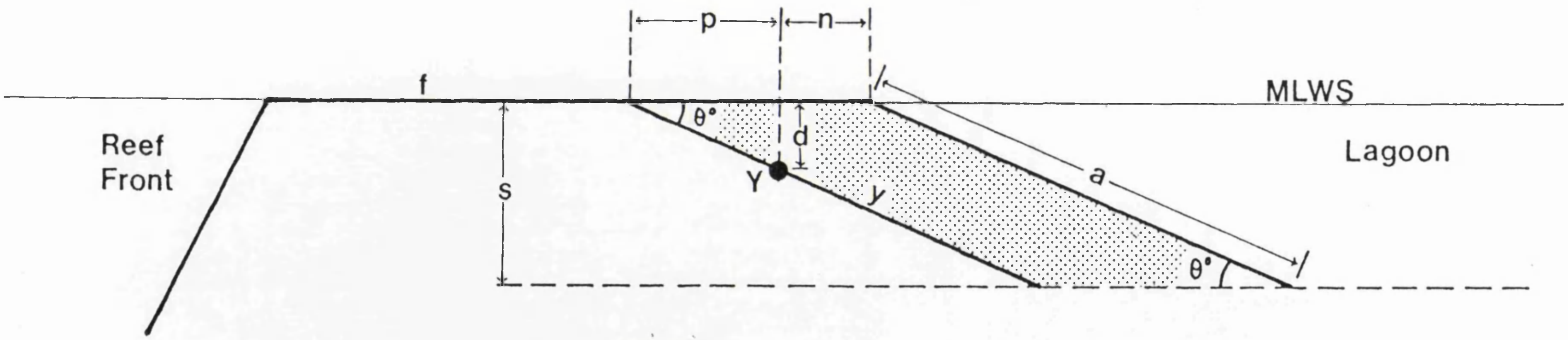
$a = 250m$. The distance along which deposition occurs, $a = \frac{s}{\sin\theta}$

The core section depths and radiocarbon dates (Table 4.2.3a and Fig. 4.2.3b) were then incorporated into this model (Table 4.2.3b). Rates of sediment accumulation calculated in this way ranged from 1.9 to 2.9m $1000y^{-1}$ (mean $2.6 \pm 0.4m\ 1000y^{-1}$).

Applying the sedimentation model (Fig. 4.2.3c) to the cross-section of Nukubuco Reef (Fig. 4.2.3b), hypothetical 'iso-time' lines were drawn through the sediment deposit using the oldest date (7030y B.P.) as a datum.

4.3. Post-Excavation Changes in Dredge Pit Topography.

During the study period dredging operations progressed eastwards along Nukubuco Reef. The profiles of two dredge pit slopes were measured



s = vertical thickness of sediment deposit, m

a = distance along which deposition occurs (i.e. lagoon slope), m : $a = \frac{s}{\sin \theta}$

d = depth of coral colony Y, m below sea bed

Y = coral colony of age Y, years B.P.

n = distance from borehole to top of lagoon slope, m

p = distance from borehole to point of intersection of surface y with reef flat (f), m : $p = \frac{d}{\tan}$

y = surface at angle θ^o from horizontal passing through Y

θ^o = angle of lagoon slope

RATE OF SEDIMENT ACCUMULATION, m $1000y^{-1} = \frac{s(n + p)}{a \times Y} \times 1000$

FIGURE 4.2.3c

Outline of model for calculation of back reef sediment accumulation rates.

See text and Table 4.2.3b

TABLE 4.2.3b. RATES OF ACCUMULATION OF BACKREEF SEDIMENT DEPOSITS BASED ON RADIOCARBON DATES FROM NUKUBUCO REEF.

d	Y	n	p	
Depth of Coral colony, m (below sea bed)	C-14 age years B.P.	Distance from borehole to top of lagoon slope, m	Distance from borehole to intersection of f and y, m	Rate of Sediment accumulation m 1000 y^{-1}
0.1	4350	200	2	1.9
0.3	4970	350	7	2.9
2.6	6370	350	65	2.6
6.1	7030	350	152	2.9
4.6	1770	0	115	2.6

See Figure 4.2.3c and text for method of calculation.

immediately that excavations were completed in June 1979. These profiles were then monitored until 1982. The site chosen corresponded with the location of the moored raft used for the hydrographic survey of the dredge pits (Plate 1.1b).

Seven metal stakes were driven into the seagrass meadow forming a grid around the edge of the dredge pit (Fig. 4.3a). This extended 20-30m into the meadow to ensure that reference points would remain even if there was a major collapse of the pit slope. Stakes were driven into the floor of the dredge pit at the bases of two "craters" lying lagoonwards of Stakes I and III.

A 50m transect line was prepared by wrapping a band of lead at every metre around an 8mm diam. polypropylene rope (pre-stretched). The lead was sufficient to make the line negatively buoyant. For each profile the line was laid from the seagrass meadow (Stakes I and III) to the deepest point of the dredge pit craters (Stakes II and IV). Water depth was measured at each mark using an SOS Helium depth gauge calibrated against a float and marked line. All depths were corrected for tidal elevation. Horizontal distance was calculated trigonometrically.

The profiles were first measured on 25th June, 1979, then remeasured on 5/21 December 1979, 2/21 September 1980 and 17/19 March 1982 (Fig. 4.3b). The angle of slope was measured as that of a line drawn from the deepest point to the rim of the dredge pit.

In June 1979 the side of dredge pit A (Stake III-IV) sloped from 0.7m to 9.3m below C.D. The angle of slope was 24°. Lagoonwards of Stake IV the sea bed rose by 1-2m forming a shallow rim around the crater, before dropping into an adjoining depression (Fig. 4.3c). By December, the angle of slope was reduced by 2°. There had been loss of 0.2-0.4m of sediment from the upper and mid sections of the slope and accretion of 0.4m at the very bottom of the pit, burying Stake IV. Events between

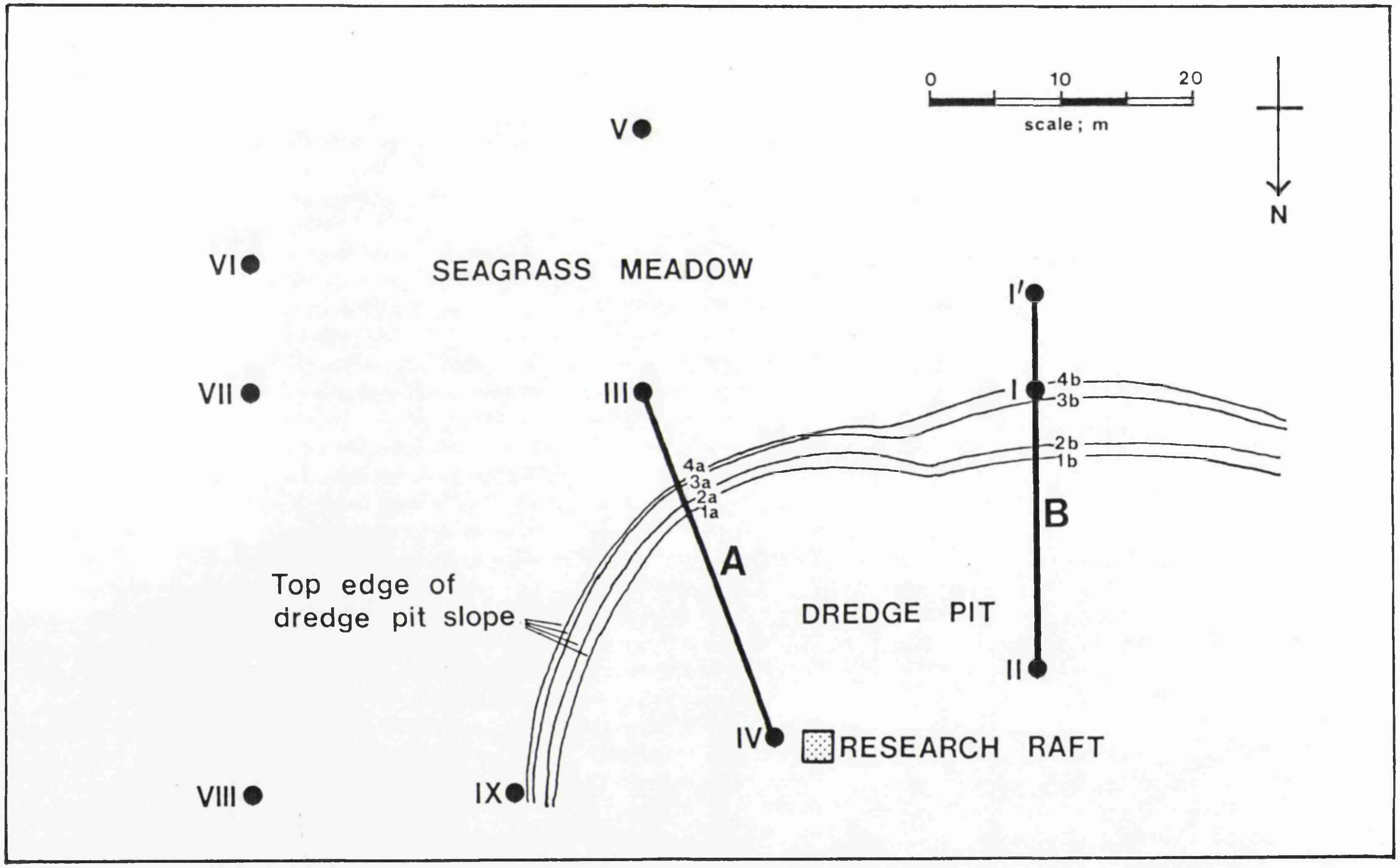


FIGURE 4.3a

i) Layout of reference stakes in dredge pit Nukubuco II and surrounding seagrass meadow.
ii) Changes in the outline of the dredge pits in the period 25 June 1979 to 19 March 1982.

1a, 1b = 25 June 1979	2a = 5 Dec 1979	2b = 21 Dec 1979	
3a = 2 Sep 1980	3b = 21 Sep 1980	4a = 17 Mar 1982	4b = 19 Mar 1982

For location of dredge pit and research raft see Plate 1.1b and Figure 1.4.2b

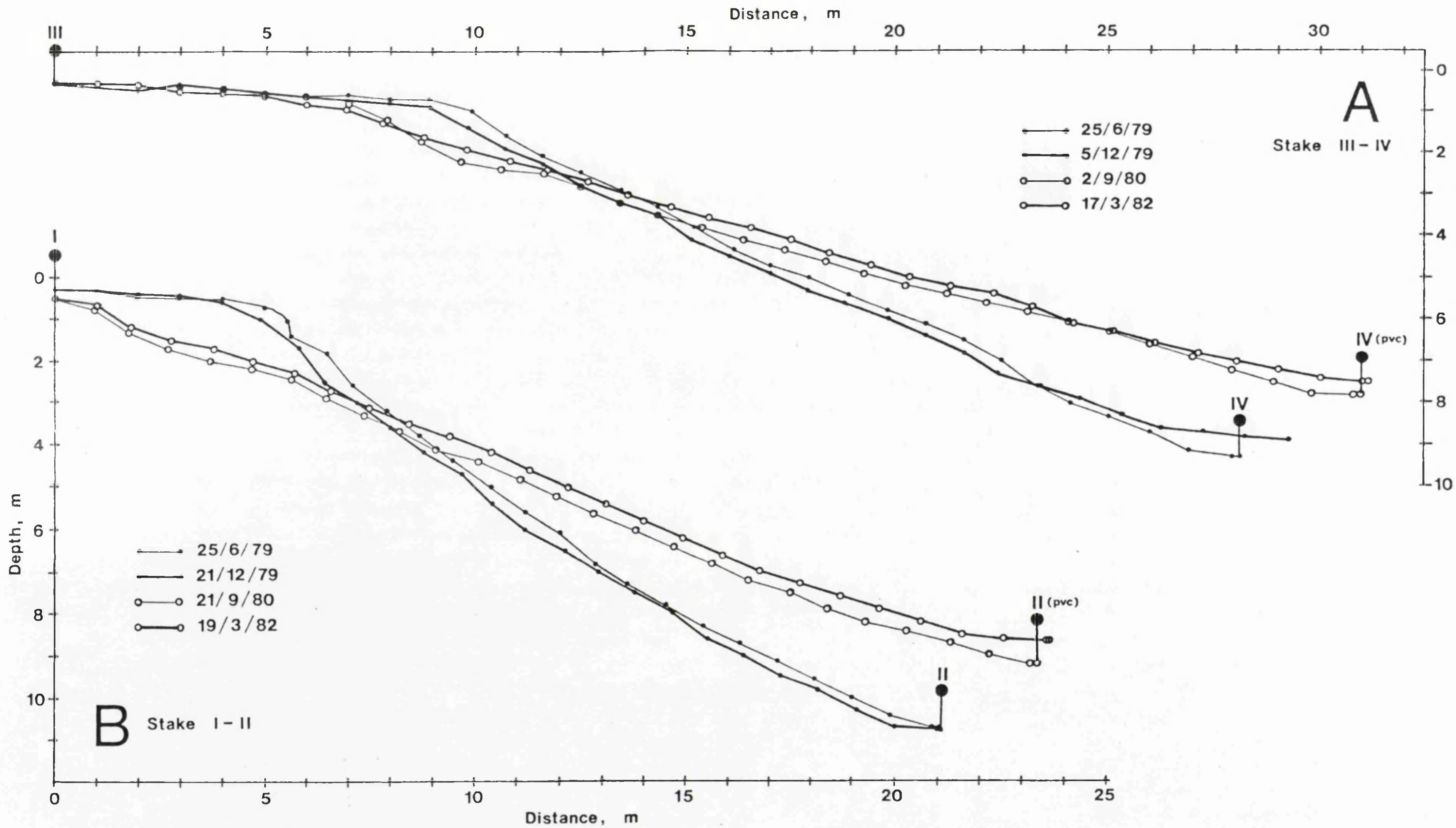


FIGURE 4.3b

Slope profiles of pits A and B, dredge pit Nukubuco II.
For location and orientation see Figures 4.3a and 1.4.2b and Plate 1.1b.

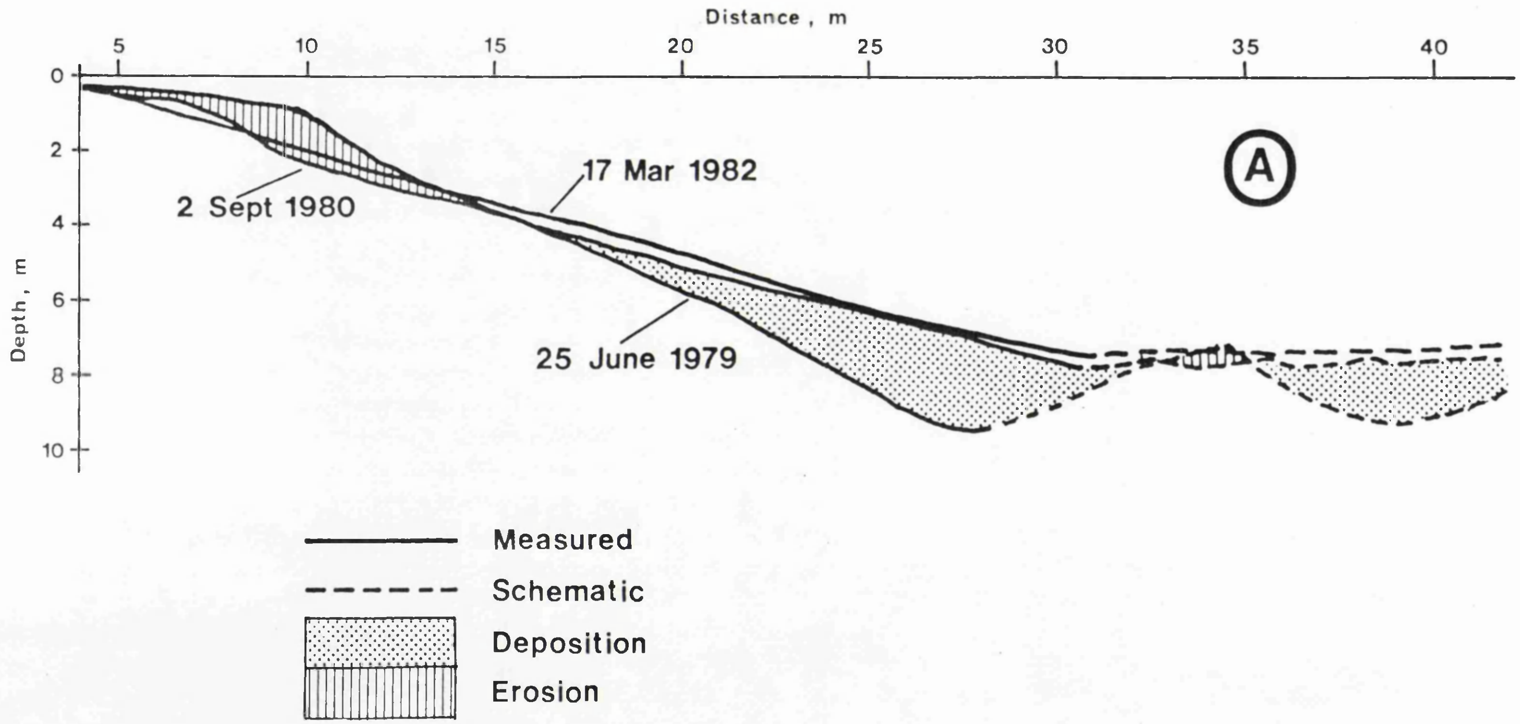


FIGURE 4.3c

Slope profiles of pit A (dredge pit Nukubuco II). Measured and schematic profiles showing overall pattern of change in bottom topography in the period June 1979 to March 1982.

December '79 and September '80 led to a marked shallowing of the dredge pit slope to 16°. A wedge of sediment was lost at the top of the slope and the dredge pit rim encroached 3-4m into the seagrass meadow. At ca. 3m below C.D. there was no net sediment change.

Below this there was increased sediment accretion with increasing water depth. At the bottom of the pit a layer of sediment 2.0m thick had accumulated above the original location of Stake IV (25 June, 1979). The deepest point of the pit was situated 3m lagoonwards of the June 1979 position. The accretion of sediment had completely infilled the 'crater' leaving a scoured bottom with sand ripples (Fig. 4.3c). When the slope profile was remeasured in March 1982 there had been a general build up of 0.2-0.3m of sediment on the middle and lower sections of the slope. Around the rim of the dredge pit there had been erosion of 0.1-0.15m of sediment.

The balance between erosion and deposition of the pit slopes is not represented quantitatively by the 2-D profile. The dredge pit was modelled as a one third section of a cone (Fig. 4.3d). The volume is given as:

$$V = \frac{\pi r^2 h}{3} \times \frac{1}{3}$$

where h is the depth of the pit (sediment depth) and r is the radius of the pit (see Fig. 4.3d). The pit volume was calculated for June 1979 and March 1982 using the first position of Stake IV as the common origin (Table 4.3a). Between June 1979 and March 1982 there was a 12% increase in the volume of the pit. Thus, contrary to the impression gained from the 2-D profiles of the slopes, there was net erosion in the dredge pit during this period.

Dredge pit B (Stake I-II) was initially deeper and with more steeply sloping sides than dredge pit A. During the first 6 months the

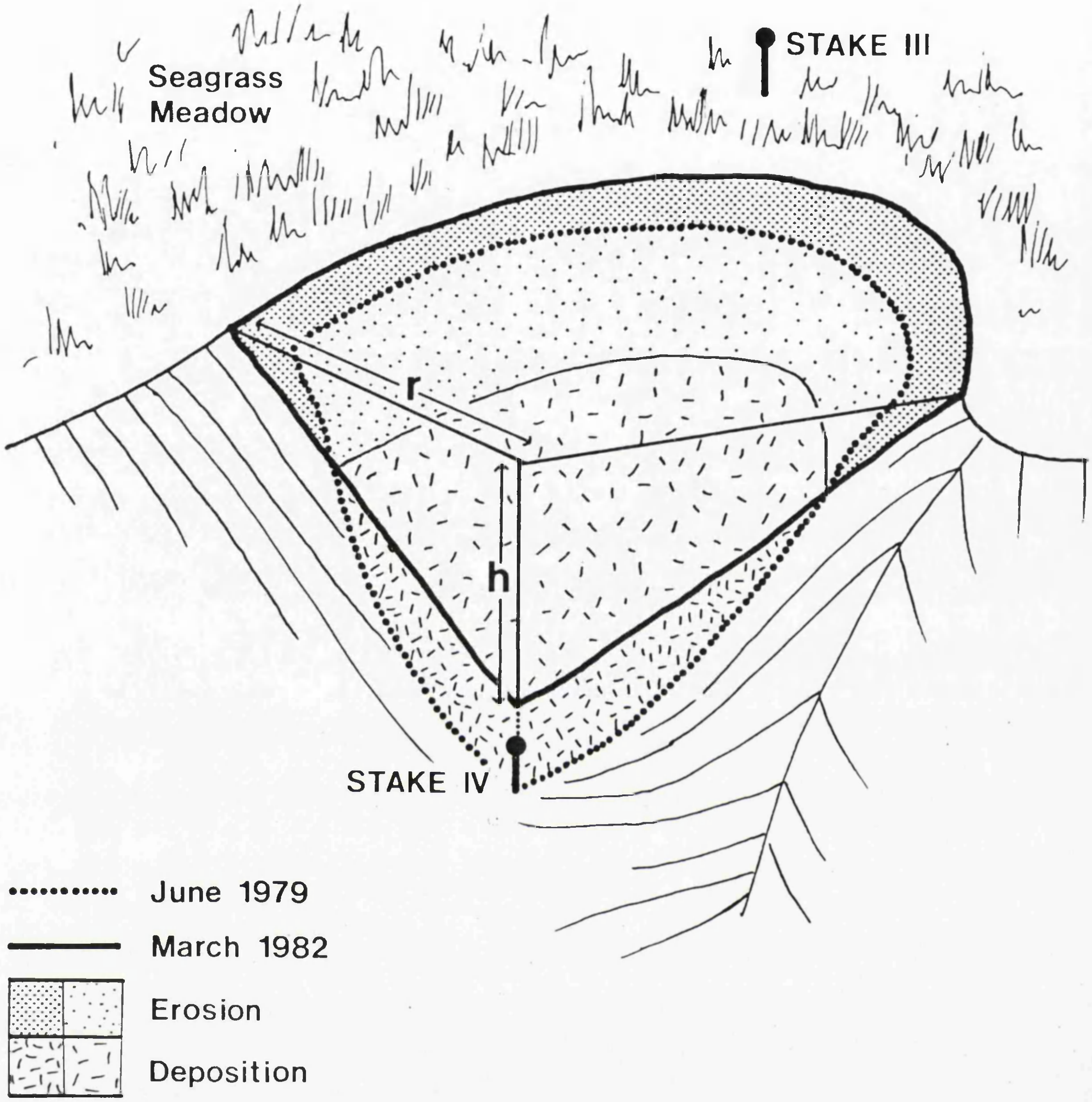


FIGURE 4.3d

Schematic 3-D configuration of pit A (dredge pit Nukubuco II) in June 1979 and March 1982.

r = radius of pit   h = depth (sediment) of pit

TABLE 4.3a. VOLUME OF DREDGE PITS A AND B ON NUKUBUCO REEF, JUNE 1979 AND MARCH 1982 (SEE FIGURE 4.3d).

		r metres	h metres	V metres^3
Dredge Pit (A)	June 1979	19	8.5	1071
Stake III-IV	Mar 1982	23	6.5	1200
Dredge Pit (B)	June 1979	16	10.0	894
Stake I-II	Mar 1982	21	7.8	1201

r = radius of dredge pit,

h = depth of dredge pit (depth of sediment).

V = volume of water contained in the pit; $V=\frac{\pi r^2 h}{3} \times \frac{1}{3}$.

Common origin, i.e., original locations of Stake IV and Stake II used for volume calculations of pits A and B respectively.

Dimensions r and h from Figure 4.3b.

angle of slope was reduced from 32° to 31° and there was loss of some 0.1-0.5m of sediment from the entire length of the slope. The ensuing pattern of change was similar to profile A, the major adjustment occurring between December 1979 and September 1980. The angle of slope was reduced first to 21°, then to 19°. However, in March 1982, despite accumulation of 2.1-2.4m of sediment, pit B was still 1.1m deeper than pit A and retained the crater-like sea bed topography (Fig. 4.3e). The volume of dredge pit B (Table 4.3a), calculated from the cone-section model, increased by 34% over the study period.

The accuracy of the slope profiling technique was tested using reference stakes (to replace the original, buried, Stakes II and IV) in the dredge pit (see Section 4.2.2.). Sediment accretion between 28th September 1980 and 23rd February 1982 was 0.23m at Stake IV (profile A) and 0.43m at Stake II (profile B). The results of the slope profiles (Fig. 4.3b) were ± 0.05m of these very precise measurements. This scale of error was insignificant by comparison to the magnitude of overall change. It was unavoidable using a measurement technique that used the water surface as a reference point.

4.4. Discussion.

Both the sieve and settling tube analyses illustrate a clear differentiation between the sediments of the seagrass beds and those of the non-vegetated sand areas. The settling velocities may be roughly equated to grain diameter using the empirical curves of Maiklem (1968) and Gibbs *et al.* (1971)(Fig. 4.1.2a and Table 4.4a). The sediment fraction with a modal settling velocity of 2-3cm s^{-1} (grain diam.; 240-260μm) constitutes 20-50% of the seagrass bed sediments but is largely absent from the non-vegetated sands. This fraction may be exogenic or endogenic in origin; whatever its source, it is trapped by the seagrass leaves and

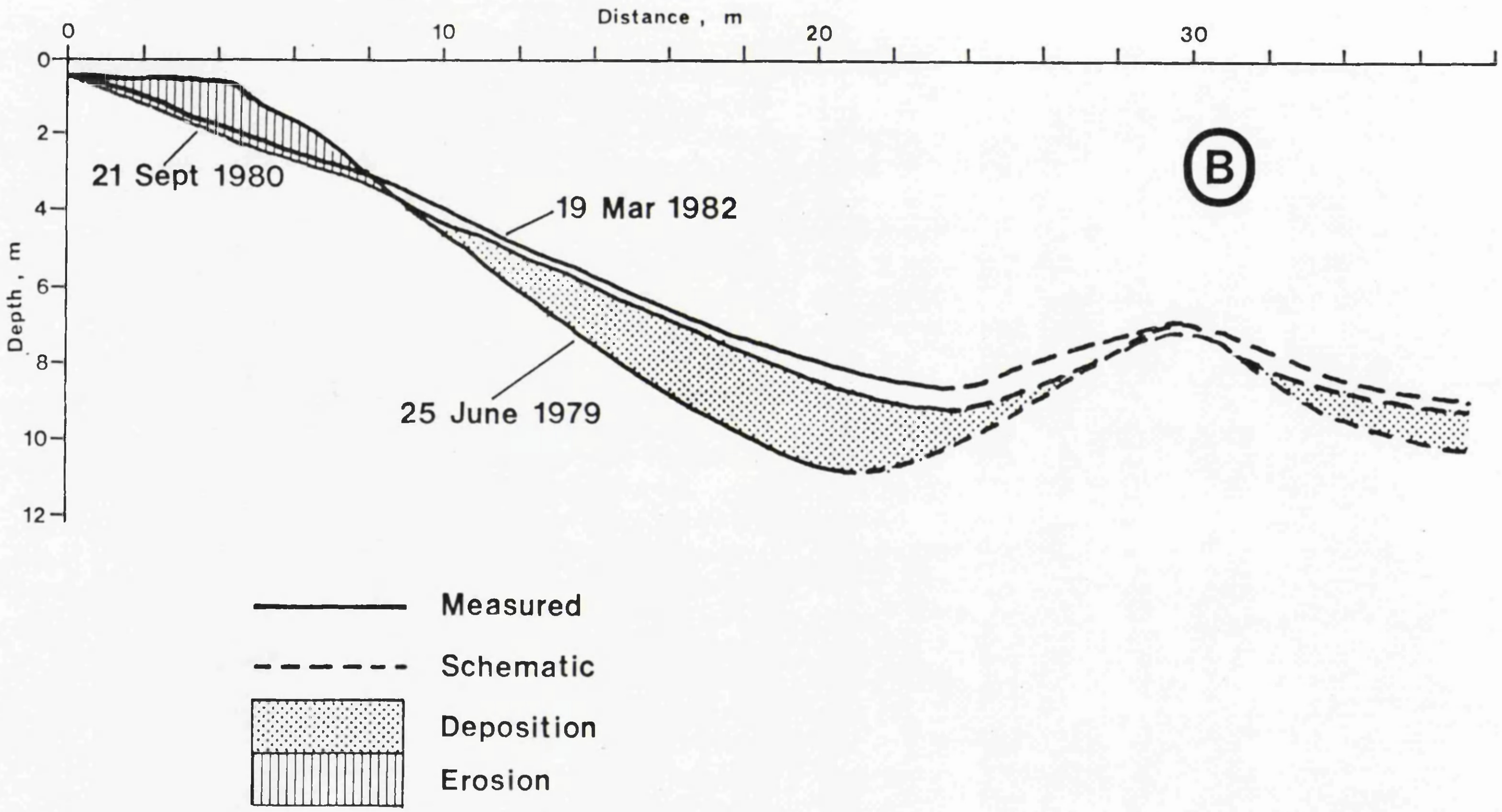


FIGURE 4.3e

Slope profiles of pit B (dredge pit Nukubuco II). Measured and schematic profiles showing overall pattern of change in bottom topography in the period June 1979 to March 1982.

TABLE 4.4a. EQUIVALENT GRAIN DIAMETERS (μm) FOR SPECIFIED SETTLING VELOCITIES FOR QUARTZ AND BIOCLASTIC GRAINS.

Settling Velocity cm s^{-1}	Grain diameter, μm			
	Single[a] glass spheres	Single bioclastic grains[b]		
		Blocks	Rods	Plates
1	115			
2.5	210	240	260	
9	580	1000	1040	2800

[a]Gibbs *et al.*, 1971.

[b]Maiklem, 1968.

bound by the root+rhizome system. The results of the sediment trap experiments indicate that some of this material (the finer fractions at least) is of exogenic origin and is deposited from suspension. The second modal sediment fraction with a settling velocity of ca. 9cm s^{-1} (grain diam.; 1,000-2,800µm) was common to both the seagrass beds and the non-vegetated areas. If of exogenic origin, these sediments are either transported in suspension during periods of high current speeds or carried along as bedload by the processes of saltation and traction. Although it is difficult to visualise the latter within the areas of dense seagrass, sediment transport can occur in these ways via the interspersed bare sand areas that constitute some 40-45% of the seagrass meadows (Section 3.2.1.1.).

In a recent study of sediment transport on a fringing reef, Roberts and Suhayda (1983) demonstrated that the lagoonwards currents are not of uniform velocity but have short-period surges related to the breaking of individual waves. During a period of average current speed of 17.3cm s^{-1} they found 1 second averaged reef crest speeds of up to 72cm s^{-1}. Thus they point out that normal reef crest processes are sufficient to transport coarse sediment into the immediate back reef, i.e., such transport is not restricted to storm events. This process of wave surging was observed in Fiji by the author, particularly on the narrower fringing reefs of SW Viti Levu. On the wide (< 1000m) barrier reefs this effect is partly filtered out although it was often noted by divers working in the thin layer of MIW (Marine Incursive Water) flowing below the LSW (Lagoonal Surface Water)(See Chapter 2). Unfortunately the continuous recording current meter used in these studies was not designed to record short-term speed variations (one 'speed mark' was marked on the paper tape for every 100 revolutions of the impellor; ca. 1 mark min^{-1} in a current speed of 0.4m s^{-1}). Roberts and Suhayda did not extend their studies to the back reef seagrass meadows.

From the brief and only qualitative observations of the seagrass flora and fauna made during this study there is no doubt that there is endogenic carbonate production within the seagrass meadow. However, the quantitative importance of this contribution is unknown.

There are absolutely no quantitative data available to describe conditions during a cyclone or tsunami. Such catastrophic events could have various possible effects on the reef. On one hand they could account for massive erosion of the fore reef and reef top, leeward transport and back reef deposition. Alternatively, the effect of exceptional suprareefal current speeds may be to resuspend fine sediments (deposited in the back reef area under prevailing conditions) leaving only the coarser fractions (of exo- and endogenic origin). Further elucidation of this complex equilibrium requires component analysis of the sediments and, ideally, observations of extreme conditions.

All the methods of measuring sediment accumulation rates had inherent drawbacks. The two main complications were the effects of bioturbation and the short (geologically speaking) experimental period.

The sediment traps were particularly prone to biological interference. Any object placed in the seagrass meadows was liable to be overturned, burrowed under, buried or taken over as a suitable habitat (particularly triggerfish and sea urchins). The jars and their supporting blocks were no exception. Although the reference stakes were taken over by the biological community, this was secondary to the major problem: short-term variations in the level of the sea bed. In one case this was brought about by erosion of the seagrass meadow, in a second by the changing pattern of crustacean mounds. In both situations negative sediment accumulation rates were recorded at the reference stakes. One of the major prerequisites for calculation of sediment accumulation rates by radiocarbon dating is that bioturbation has not destroyed the original depositional fabric (Davies, 1982): this is by no means certain.

In the outline reef drilling programme, 6 boreholes were proposed, 3 on Nukubuco Reef and 3 on Namuka Reef. In the event, a total of only 3 holes were drilled with core recovery increasing with each hole; 0, 2·5 and 8% recovery for Boreholes A, B and C respectively. These were the first reef drilling operations to be carried out by the Mineral Resources Department (Overseas) and as was pointed out by Holmes (1980), "it is difficult to gauge whether the better recovery reflects a different geology or improved drilling expertise".

With only one borehole on Namuka Reef, interpretation is limited to the calculation of a vertical rate of sediment accumulation. The reef configuration at Borehole C can be termed neither barrier nor fringing. The complexity of the structure of the region was demonstrated when a test drill hole less than 100m to the west of Site C struck bedrock at 10cm below the reef surface. This was thought to be contiguous with the formation giving rise to Namuka Island, Koro-ne-belo lele/lailai and Muaivuso Point (Note bedrock outcrops on the reef along this line; Plate 1.1a). The radiocarbon ages of the two deepest core samples from Borehole C were inverted. Both samples were cores of a massive coral, *Pavona* sp. It may be that one of the samples was contaminated, giving an erroneous date. Alternatively the inversion may have been actual; the upper colony being transported and deposited some centuries *post mortem*.

From the radiocarbon dates for Nukubuco Reef, mean sediment accumulation (net deposition) rates were calculated as 3.2m $1000y^{-1}$ (conventional "vertical accretion") and 2.6m $1000y^{-1}$ (sediment wedge model). By comparison, mean gross deposition rate estimated by sediment traps was 20-27m 1000y^{-1} (expts. SED 1 and SED 2 respectively). Several possible explanations might account for this disparity:

1. The sediment traps gave a true measure of the downward flux of sediment (gross deposition) during the experimental period but ca. 90% of this material was destined to be eroded and transported away at a later date.
2. The sediment traps oversampled the suspension load, i.e., the downward flux was overestimated.
3. The sediment traps were affected by sediments resuspended by bioturbation.
4. The coral colonies cored in the boreholes were reworked colonies swept into the seagrass meadows and incorporated into more recent sediments, i.e., the radiocarbon dates were consistently older than the sediments in which they were found.

It is not possible to say with certainty whether the dated colonies of *Diploastrea heliopora* and *Porites* sp. were deposited in growth position. Both these corals are characteristic of back reef lagoon slopes although at present *D. heliopora* is not found in this zone of Nukubuco Reef. However, since the sampled colony weighed 2-3 tonnes (dredge operator, *pers. comm.*) it is unlikely that it had travelled far. A detailed geomorphological and archaelogical survey by Parry (1977) has shown that as recently as the 18th Century, the major distributory of the Rewa (the Wai ni ki; now completely filled and abandoned) drained into Bau Water on the E coast of Viti Levu (Fig. 4.4b). The shift from this channel in favour of the present Rewa (the Wai Levu) probably occurred ca. 1793 during a catastrophic flood. The recurrence of truly devastating flooding on a scale sufficient to cause major changes in the distributary pattern

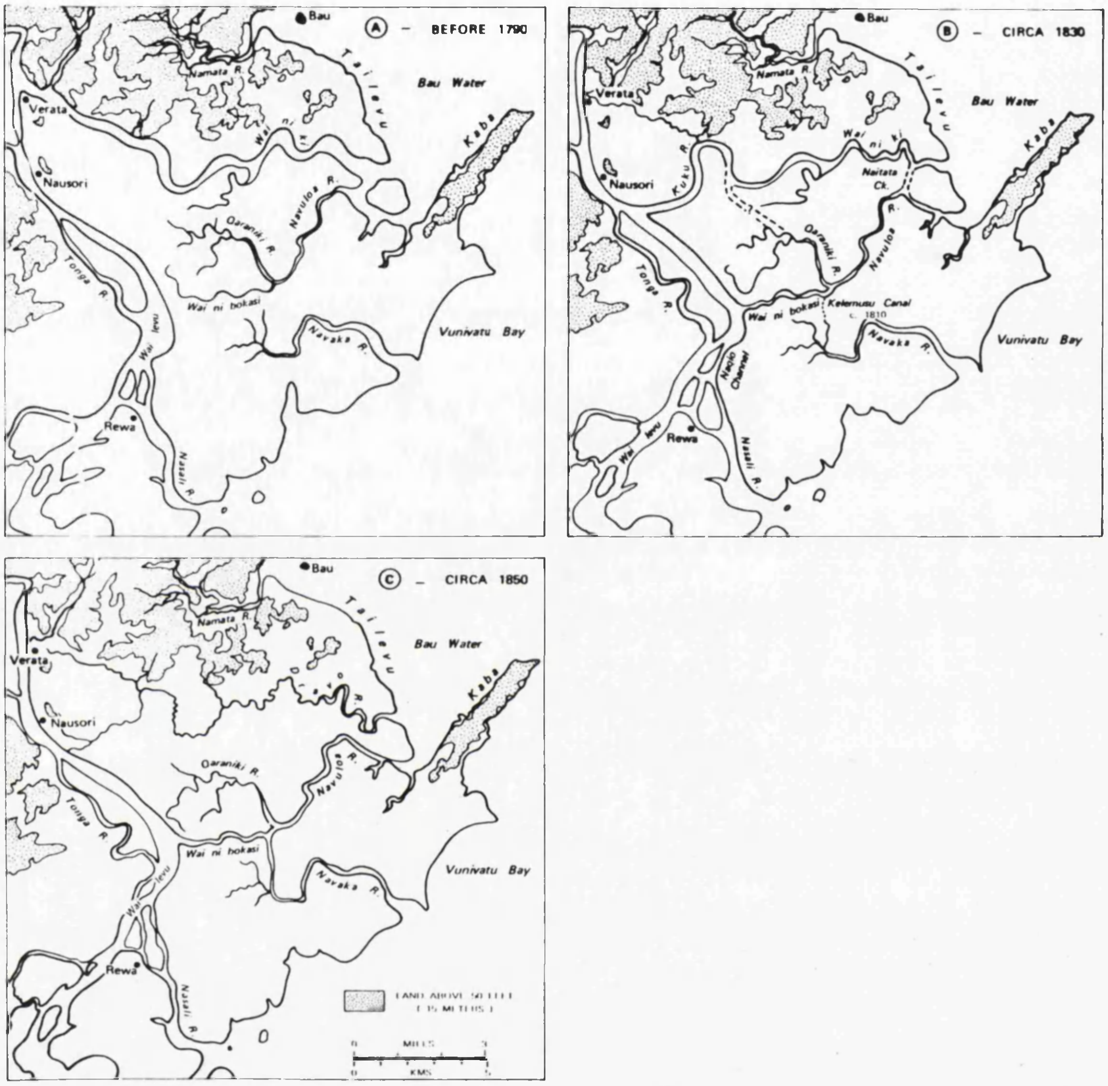


FIGURE 4.4b

Major changes in the distributary pattern of the Rewa delta in the late eighteenth and nineteenth centuries (Parry, 1977).

of the delta is put in the order of 200-500 years or longer. This has great significance on the interpretation of reef development in SE Viti Levu, particularly Laucala Bay. The Lagoonal Brackish Surface Water (LSW) that dominates the present hydrographic regime in the Bay (Chapter 2) was probably of much lesser importance as recently as 200 years ago. 1000 years ago it may be that there were no major distributaries entering Laucala Bay. It is clear then that the lagoonal hydrography, particularly the influence of river discharge, has undergone several abrupt and major changes during the period of Holocene reef development. This must have had profound effects on the reef community. Thus simply because *D. heliopora* is not found on the back reef lagoon slopes today does not mean that it was not to be found there ca. 1770y B.P. Small colonies of *Porites* are found in the seagrass meadows in Laucala Bay and at Namuka Island.

It is apparent that interpretation of the sediment trap data must be qualified by a series of provisos. Some measure of gross deposition was obtained but in the absence of data concerning erosion, no estimate can be made of net deposition (accumulation). On account of the brief interval between measurements, the data obtained from the reference stakes was useful only in the dredged areas. Of the three techniques, the radiocarbon dating of the cores provided the most rational information on sediment accumulation rates. The values obtained from this data (2.4-3.2m $1000y^{-1}$ and 2.6m $1000y^{-1}$) are of the same magnitude as lagoonal sedimentation rates for One Tree Island estimated as 1.5m $1000y^{-1}$ (budget studies; Davies, 1977) and 1.7m $1000y^{-1}$ (radiocarbon dating; Marshall and Davies, 1982).

Evidence of the pattern of post-glacial sea level change is reviewed for the Great Barrier Reef by McLean et al. (1978), Thom and Chappel (1978) and more generally by Hopley (1978). In the Fiji Group, sea level probably rose to -20m (relative to present) ca. 9,000y B.P., to -10m ca. 7,800y B.P., reaching present day level (possibly 1m higher than present; see Taylor, 1978) ca. 6,000 to 5,000y B.P. At One Tree Island (Great Barrier Reef), Holocene reef growth began at -12m (relative to present sea level) ca.8,000y B.P.(Marshall and Davies,1982); it is probable that barrier reef formation in Fiji commenced at approximately the same time. The oldest radiocarbon date obtained on Nukubuco Reef was 7030y B.P. at a depth of 6.1m below the sea bed (7.1m below M.S.L.) and at a distance of 850m from the reef crest. From the limited evidence presented in this study it appears that back reef sediment accumulated at a fairly steady rate with leeward extension of the reef at a rate of ca. 70m $1000y^{-1}$ (Fig. 4.2.3b).

In the absence of more dates, no further interpretation is warranted. However, it is speculated that:

(1) The Pleistocene karst surface (the "Thurber Discontinuity") lies within a short distance of the bottom of Borehole B, i.e., no more than 10m below the sea bed.

(2) To account for the major bulk of the reef seawards of Borehole B, much of the reef is of Pleistocene (or earlier) origin, i.e., the Thurber Discontinuity lies close to the present reef surface. Part of the present, exceptionally wide, reef flat is possibly a relict reef surface.

Examination of the dredge pit slopes showed that, in both the pits studied, a major adjustment took place between 6 and 16 months after dredging. The delay in the initiation of this change suggests that it was not prevailing conditions but a "one-off" hydrographic extreme that triggered the event. Whatever the cause of the change in slope, the apparently rapid rate of sediment accumulation at the pit bottom was attributable not to a influx of new sediment (i.e., a replenishment of the sand resource), but to a relocation of existing back reef deposits.

5. Summary Discussion

CHAPTER 5. SUMMARY DISCUSSION.

The inception of this research was a *Draft Outline of a Study of the Impacts of Current and Proposed Coral Sand Dredging in the Suva Region* (Appendix IIa), a document prepared by the then Fiji Government Environmental Advisor, Dr. G.B.K. Baines. The study outline was broken down into three components: economic, social and environmental impacts. The scope of the intended work was extremely broad, encompassing several diverse fields of research and anticipating input from professional geologists, biologists, oceanographers, sociologists and economists all working in liaison with Fiji Industries Ltd. (Appendix IIb). The work presented in this thesis deals primarily with the *environmental impacts* of the sand dredging: past, present and proposed. For convenience of reference, this discussion is arranged in a format similar to that of the original proposal.

The major environmental impacts are expected to be occasioned by:

(1) fine sediments disturbed during dredging.....(Baines, 1977).

Fine sediments resuspended during sand excavation or spoil disposal operations are frequently a major environmental hazard. Excessive sediment deposition rates and lack of light (on account of high turbidity) are important factors limiting coral reef development (e.g., Marshall and Orr, 1931; Roy and Smith, 1971; Dodge et al., 1974; Loya, 1976). Some benthic invertebrates including reef corals, can also be affected adversely by sediment deposition (Brehmer, 1965; Bakus, 1967; Kaplan et al., 1974). Sedimentation is a natural process occurring under both prevailing and episodic, catastrophic, conditions. However it is well documented that increased sedimentation on account of dredging activities may have an adverse effect on coral reef community structure and growth (e.g., Brock et al., 1966; Grigg, 1970; Levin, 1971 (literature review); Endean, 1975;

Johannes, 1975; Dodge and Vaisnys, 1977; Bak, 1978). Increased turbidity created by the dredging of coral sands has also been shown to cause a reduction in lagoonal primary productivity (Ricard, 1980).

However, the dredging situation in Fiji is not directly comparable to any of those studies referred to above. Several key points need to be considered:

1. On account of the prevailing oceanographic regime (Chapter 2) the bottom currents (Marine Incursive Water; MIW) are invariably lagoonwards, i.e., away from the reef, normally ranging in speed from 0.1 to 0.3m s^{-1}.
2. With the exception of isolated coral bombies in the lagoon, the back reef slopes are largely devoid of coral colonies (in both control areas and downstream of dredged areas).
3. On account of the rapid development of the Rewa River catchment area (see Fig. 1.2.5a and discussion in Section 1.5.) the surface waters (Lagoonal Brackish Surface Waters; LSW) of the bay are highly turbid, masking any sediment disturbance caused by dredging.

Thus there is no evidence that, in the Fiji situation, there is any detrimental effect on coral reef growth as a result of fine sediments disturbed during dredging. Nor, since, at all times of reef immersion, the seagrass meadows are swept by incursive MIW, is there any evidence of a measurable reduction in sea bed irradiance in that zone. It should be noted that the present method of dredging is particularly "favourable" environmentally. The clamshell dredge picks up a bucket of sand and deposits it in the barge with a minimum of sluicing away of fines. Were a cutter-suction dredge to be used then the sand would be raised to the surface in suspension up the dredge pipe; for every $1m^3$ of sand extracted, up to $5m^3$ of water laden with fine sediments would be sluiced over the sides of the barge (the distance from the reef to the shore renders it impractical to run the dredge pipe ashore to settling ponds). If such a process were to be adopted, then the amount of sediment resuspended during dredging would be increased by an order of magnitude or more.

The back reef sediments are non-cohesive, highly porous and a very pale grey in colour. There is no evidence of disturbance of toxic anaerobic layers during the dredging operations.

In the locations where dredging operations ceased some years ago it is notable that where a suitable substrate is available for settlement, the environment is very favourable for coral growth (Section 3.4.1.).

At the site of proposed sand extraction at Namuka (Fig. 1.4.2b) the oceanographic regime is different to that of Laucala Bay and Suva Harbour, notably by the absence of the LSW mass (Section 2.2.3). Fine sediments disturbed in this region are more likely to be noticeable since they will not be masked by suspended sediment of terrigenous (fluvial) origin. The area most likely to be affected is the lagoon lying to the S of Namuka Island (Fig. 1.1b). However, this region is constantly flushed by MIW, wave-driven across the reef, leaving the lagoon via Namuka Passage into the open ocean. An estimate of the input of water to the lagoon may be calculated as follows:

estimated length of reef from which MIW is channelled into lagoon.*1	2500m
estimated mean water depth over reef	1m
estimated duration of flow*3	8.3h*2
estimated mean speed of flow*3	$0.15 m\ s^{-1}$

*1 : Figure 1.1b and Plate 1.1a

*2 : 2/3 tidal cycle.

*3 : Section 2.2.3. and Figure 2.2.3a.

Under such conditions, the water flow into the lagoon during one tidal cycle would be 1.1 x $10^7 m^3$. The lagoon covers an area of ca. 0.45km^2 (Fig. 1.1b) and its depth ranges from 8 to 26m (Chart BA 1757). Using an estimated mean depth of 18m, the volume of water in the lagoon is ca. 8.1 x $10^6 m^3$. Thus, the estimated input of water during one tidal cycle is comparable to, possibly in excess of, the volume of the lagoon. Although the lagoon has an entrance sill at a depth of 9m (Section 1.1) it is considered unlikely that a stagnant layer would develop at depth. No evidence of such a structure was observed on SCUBA diving in the lagoon. Based on the reef top flow observations (Section 2.2.3) and the calculations above, this lagoon is thought to be regularly flushed, possibly daily. Adverse effects of sediments resuspended during dredging (using the present method) are not foreseen as a major hazard.

The major environmental impacts are expected to be those occasioned by:

> *(2) changes in water circulation and patterns of sedimentation resulting from removal of sand and blasting of passages*..............(Baines, 1977)

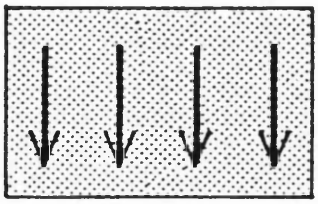
Comparison of the oceanography of the present dredge pit (Nukubuco Reef, Section 2.2.4) and the control site on Suva Reef (Section 2.2.2) indicates that in Laucala Bay the pattern of back reef water movement is significantly altered by the excavation of pits. The changed pattern of MIW : LSW interaction results in the intensification of bottom currents and the impoundment of a deep layer of turbid LSW within the dredge pits. The former leads to bottom-scour and displacement to the right of the DEPOSITION $\rightleftarrows$ EROSION equilibrium. The chances of biological settlement are also impaired. The latter causes a disproportionately large reduction in submarine irradiance (by comparison to the same depth of MIW), thereby reducing the potential for re-establishment of the seagrass meadows and certain corals (on account of the requirements of their zooxanthellae).

The pattern of dredging to date has entailed the excavation of continuous pits. It has been suggested (Baines, 1977; and others) that some of the adverse effects of dredging (then unknown) might be alleviated by changing the dredge pit configuration. In Fig. 5a consideration is given to several alternative patterns of excavation. The main drawback with all the alternative methods is that of access to the pits; the pontoons and sand barges are relatively unmanoeuvrable vessels with high windage and shallow draft. Some rather attractive "drawing board" ideas are quite inapplicable in the field situation. Furthermore, at least one of the configurations, that of elongate pits, orthogonal to the reef front, would lead to increased scour of the pit floor. The biological importance of these different patterns is also discussed (Fig. 5a and below).

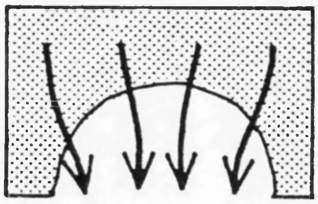
The changes in the pattern of water movement are very localised and there is no evidence that the lagoonal circulation as a whole is affected.

In the more enclosed areas of Lami and Waiqanaki Reefs (dredge pits Waiqanaki I-III) the oceanographic situation of each pit is quite different (see Section 2.3 for discussion). The reef front is progressively more exposed moving to the west and maximum current speeds were observed where the water draining from a large expanse of the 'fringing' type reef off Waiqanaki/Muaivuso Villages is funnelled through dredge pit Waiqanaki III.

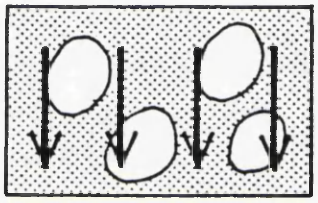
It has already been noted that the LSW mass is not generally observed at the site of the proposed excavation at Namuka (this discussion and Section 2.2.3). There is no evidence to suggest that, subsequent to dredging there, there would be any current speed intensification equivalent to that observed in Laucala Bay. Moreover the excavation of the Namuka seagrass meadow is unlikely to funnel the reef top currents (cf. dredge pit Waiqanaki III). In fact, the perimeter of the deep lagoon will be



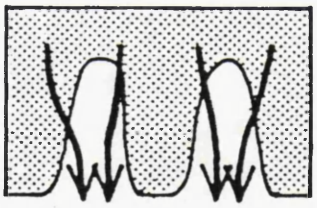
CONTROL: Undisturbed seagrass meadow. Current vectors parallel.



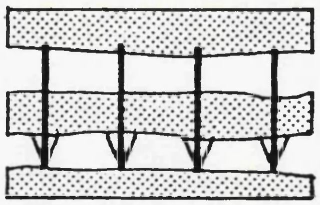
CONTINUOUS PIT: Present method of dredging. Easy access. Some deflection of current vectors (= scour). Vegetative seagrass material for recolonization only available around perimeter of pit.



ISOLATED PITS: Difficult access. Little deflection of current vectors (= no scour). Maximum amount of vegetative seagrass material available for recolonization.



PITS ORTHOGONAL TO REEF FRONT: Reasonable access. Deflection of current vectors leading to scour of pit floors and displacement of recolonizing seagrass material.



PITS PARALLEL TO REEF FRONT: Extremely difficult access. Little deflection of current vectors. Improved prospects of infilling and seagrass recolonization.

FIGURE 5a

Possible alternative configurations of dredge pits increased and the current speed at any one point along the edge is likely to be reduced.

The patterns of sedimentation are complex, there being two distinct sources of sediment; exogenic (that produced elsewhere and transported to the area of deposition) and endogenic (that produced and deposited *in situ*) (see Section 4.1.). This study has not elucidated the relative importance of these two sources. However there can be no doubt that sedimentation is increased in the presence of seagrasses. There is not only the endogenic production of biogenic sediment but also the combined effects of trapping and stabilization. Removal of the seagrass leads to a reduction and change in the pattern of sedimentation.

Quantitative sediment budget studies of the extensive, morphologically diverse reefs were beyond the scope of this study (cf. Baines, 1977). Of the sedimentation rate studies the results of the sediment trap experiments (Section 4.2.1.) were an order of magnitude greater than those of the radiocarbon dating technique (Section 4.2.3). In the absence of further information on the erosional/depositional processes, the more conservative results of the latter must be adopted. The accumulation rate thus obtained, 2.6m $1000y^{-1}$, is a measure of the slowness of deposition by comparison to the rate of sand extraction. The possibility of re-accumulation of sand in the already dredged areas, with view to re-excavation, is quite unrealistic. This is supported by the observations of reference stakes (Section 4.2.2) and the post-excavation changes in dredge pit morphology (Section 4.3). Although, in the latter case there was a rapid elevation of the pit floor, there was no evidence of net deposition in the pit as a whole.

The back reef sediment is produced either upstream of, or within, the depositional area. With respect to back reef deposition of biogenic sediments, each discrete reef, separated as they are by deep channels, can be considered as an individual depositional unit. On Nukubuco Reef it is possible that excavations could affect the mobile sand cay, Nukubuco Island. However, at present, the island is increasing in size (Section 1.1) and there is no evidence that sand excavation has had any detrimental effect. Since the reef top current streamlines in the area of dredging are orthogonal to the reef (Plate 1.1b), no future effect is foreseen. It has been suggested that one consequence of the sand dredging has been the relocation of the sand cay on Makuluva Reef (Section 1.1). This is one of the several unsubstantiated accusations levelled against the sand dredging operations. The movement of the Makuluva sand cay commenced during the 1950's, long before any sand dredging operations were initiated. It is suggested by the present author that this destabilization was caused by either the tsunami or the tectonic movement associated with the 1953 Suva earthquake (see Section 1.3.1). On consideration of the reef top hydrography, the correlation by Owens (1971) between sand dredging operations and the presence, 3km distant,of excessive populations of the Crown-of-Thorns starfish (*Acanthaster planci*) are unfounded (high population levels were recorded at many other remote locations in Fiji).

With reference to the site of proposed dredging at Namuka, little is known of the pattern of sediment movement save for that evidenced by the current streamlines on the reef (Plate 1.1a). From the aerial photographs and hydrographical observations there is no evidence that enlargement of the lagoon (S of Namuka Island) will have any affect on the mainland shoreline. The possible effects on the sediment budget of Namuka Island are unknown. However, being a high island, shoreline alterations cannot be extensive, the only major beach being on the NW corner of the island.

The major environmental impacts are expected to be those occasioned by:

(3) changes in the marine food resource resulting from substrate modifications............. (Baines, 1977).

The biological impact of the dredging operations to date has been concentrated on the seagrass ecosystem (Section 1.4.2). Concordant with parallel communities elsewhere in the world, the seagrass meadows in Fiji are highly productive. Complete turnover occurs approximately every 55 days (6.7 times y^{-1}) and leaf productivity in the study area is estimated to be 157 tonnes C y^{-1} (Section 3.3.5).

The structure and energy pathways of the system are intricate and beyond the scope of this work. However, the effects of sand dredging are very clear: within the dredged area there is complete removal of the seagrass meadows; conversely, adjacent to the pit edges the seagrass is apparently unaffected. The effects of removal of the seagrass meadows are several (for full discussion of the functional role of the seagrass community, see Section 3.3):

(i) Reduction in the potential reservoir of fish and shellfish available to the local subsistence fishery.

(ii) Reduction in the feeding area available to wider ranging reef animal species. Depending on the percentage loss of habitat there may be a reduction in the recruitment of reef fish reliant on the seagrass meadows as a nursery area.

(iii) Immediate loss of the endogenic sediment production associated with the seagrass community.

(iv) Modification of the depositional hydrodynamic environment.

From a biological viewpoint, proposals for the management of sand dredging involve several considerations:

1. LOCATION. On account of differences in reef morphology the seagrass meadows are distributed unevenly through the study area: they are considerably more extensive on Nukubuco and Suva Barrier Reefs than on the Lami/Waiqanaki/Namuka Reef complex. Dredging operations have already removed a significant percentage (>50%) of the seagrass meadows from Lami and Waiqanaki Reefs (Section 1.4.2). The damage to meadows on Suva and Nukubuco Reefs has been in the range 1 to 5% only. Although it is estimated that the sand reserves on Namuka Reef (Section 1.4.3) will be sufficient for the estimated requirement of the Cement Industry during the next 25 years, it must be borne in mind that this projection is conditional on the excavation of the entire seagrass meadow in the region. Thus, although it was estimated (Section 1.4.3) that, by the year 2008, the dredge pits will have affected some 14.3-15.5% of the seagrass meadows (in the study area), the impact of this will be weighed heavily on the smaller seagrass meadows to the W of Suva. The consequences of such a plan (loss of subsistence fishery, etc.; see above) should be weighed against the reasons for not dredging the extensive sand deposits indicated by the seagrass meadows on Suva Reef (Fig. 1.4.2a), e.g., conflict with the requirements of the tourist boats operating between Suva and Nukulau Island.
2. METHOD. As pointed out above (this discussion), the present method of dredging causes considerably less damage than would the most probable alternative, a cutter-suction type dredge.
3. DEPTH. The present working depth is limited to ca. 10m below C.D. (Section 1.4.2). The possibility of natural recovery (or artificial transplantation) of the seagrass would be greatly increased if the depth of dredging was limited to the compensation depth for seagrass growth (e.g., Swain and Hull, 1980). The maximum natural depth penetration of

the seagrass meadows in the study area does not exceed C.D. -4m (see Fig. 3.2.1.1a and Section 3.2.2). Extraction of a unit volume of sand from a pit with a maximum depth of 4m (below C.D.) would affect a surface area some 2.5-3.0 times greater than that excavated from a pit 10m deep (below C.D.). Thus there are two possible strategies:

D1	D2
MAXIMUM working depth (C.D. -10m)	REDUCED working depth (C.D. -4m)
↓	↓
MINIMUM surface area (= seagrass meadows) affected	INCREASED surface area (= seagrass meadows) affected.
↓	↓
NO seagrass recolonization while pitfloor remains deeper than compensation depth	POSSIBILITY of restoration of seagrass meadows.
↓	↓
POSSIBILITY OF rehabilitation by construction of artificial reefs (see below)	POSSIBILITY of rehabilitation by construction of artificial reefs (see below).

It was estimated (Section 1.4.3) that using the present method of dredging (Strategy DI) some 14.3-15.5% of the seagrass meadows in the study area will have been affected by the year 2008. By adoption of Strategy D2, this figure would be increased to 35-45% of the seagrass meadows. Although the chances of natural recolonization would be increased, observations made during this study suggest that it would be a very protracted process, particularly since the lowered sea bed would be at the extreme limit of depth penetration of the seagrass (i.e., non-optimum conditions).

4. REHABILITATION. Whichever dredging depth/area strategy is chosen, several possibilities exist to accelerate the return of the dredged areas to biologically productive conditions.

i. Natural revegation: Recolonization is dependent on an adequate supply of vegetative seagrass material (no evidence was found of propagation of *Syringodium isoetifolium* from seed; Section 3.2.1.1) and conditions favourable for growth, i.e., substrate, depth, light, etc. (see Section 3.2.2). The supply of vegetative material may be controlled by alteration of the dredge pit configuration (Fig. 5a).

ii. Seagrass transplantation: The restoration of the original habitat is an extremely desirable objective. However the problems of transplanting are clearly numerous (Section 3.7.1) and not fully understood. The installation of the transplants is a sophisticated operation and only achieved using SCUBA and trained personnel, facilities not readily available within the Cement Industry. Without a marked reduction in the depth of dredging (Strategy D2) and allocation of substantial funds and expertise, rehabilitation by manual transplanting of seagrass is considered to be an unrealistic proposition.

iii. Artificial reefs: This rehabilitation technique offers several advantages; it achieves an immediate result, requires a minimum of observation or maintenance and within a short period (1-2 years) initiates an exploitable subsistence fishery in a previously barren area. The construction of the reefs requires surface support from a tug and barge and onshore support from a crane and road transport; these facilities and the necessary operating skills are already available within the Cement Company. Should it be desirable, in the future, to re-work the pits, there is no doubt that a major artificial reef construction would severely complicate, and probably preclude, such an operation. However, the evidence from the sediment accumulation rate experiments (Section 4.2 and this discussion, above) indicates that the dredge pits will only fill up over a time period of many centuries. Since, at present, the depth of dredging is limited to 10m by the equipment available in Fiji, it is unlikely that re-dredging to deeper depths using this equipment will be viable (the dredging operation becomes progressively more expensive with increasing depth on account of the time and energy required to lift the material to the surface) The possibility of future investment in new dredging equipment should be considered before constructing extensive artificial reefs.

The potential for rehabilitation in any one area depends on the local hydrography (water masses, currents, turbidity), substrate and the depth and configuration of dredge pits. Post-dredging hydrographic conditions at the proposed Namuka site are likely to resemble most closely those of dredge pit Waiqanaki III, although current speeds will probably be lower (see above). If dredging is carried out in a manner similar to the present operations (Strategy D1) then construction of artificial reefs can be expected to produce favourable results. The varied success of different substrates (Section 3.7.2 amd 3.8) should be taken into account.

No major change in the local hydrography is foreseen as a result of deepening the Namuka boat passage. However it is strongly recommended that all the excavated material should be removed completely and not dumped as a levee shorewards of the channel (as was the case when the channel was dredged from dredge pit Waiqanaki I, via Waiqanaki II, to Rattail Passage). An unbroken levee constructed along the length of the proposed channel would significantly affect the reef top circulation. In spite of this precaution it should be noted that, on account of wave-driven incursive waters (MIW) spilling off the reef top into Rattail Passage and Namuka

Lagoon/Harbour (Section 2.3), the proposed passage is likely to be subjected to strong currents, particularly on the ebb tide and during conditions of high wave energy. Construction of this channel should be seen as a beneficial consequence of dredging in the Namuka area. Sheltered access to Suva from the west (presently only possible for punts during the period HW ± 3hrs) will be greatly improved. The benefit of such a development for the people of Muaivuso Village should be noted.

In conclusion, it is important to remember that sand extraction is just one of many pressures borne by the nearshore reefs close to Suva (industrial and urban wastes, river borne terrigenous sediments disturbed by inland development, fishing and reef gleaning, etc., see Owens (1971) and Section 1.5., this study). The dredging is clearly visible in terms of the operation (traffic of pontoons and barges) and its results (discrete, identifiable pits). The effects of other potentially damaging influences are harder to quantify or document. In many cases the cause/effect relationship is far less tangible; whilst the dredge pits are there for all to see, the possible reduction of the seagrass compensation depth on account of increased turbidity of the Lagoonal Brackish Surface Water (LSW)(e.g., as a result of soils disturbed within the catchment area of the Rewa River) is far more difficult to detect. It is possible that the latter may eventually (or already have done so) cause a greater reduction in the seagrass meadows than the former.

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Appendices

APPENDIX I.

Aerial photographs covering the Nukulau Island to Namuka Island region.

Held at the Department of Lands and Surveys, Government House, Suva, Fiji Islands.

1951		Scale 1:16,000
F 3/I	002 - 004.	
F 11/I	001 - 008.	
F 20/II	063, 064.	
F 22/I	030 - 039.	
F 25/I	034	
1954		Scale 1:40,000
11/FJ 16	001.	
11/FJ 17	140 - 142.	
11/FJ 19	002 - 004, 026, 058.	
1967		Scale 1:24,000
95-FJ 3	001 - 003.	
95-FJ 36	012, 045 - 047.	
1973		Scale 1:80,000
V39A RAF 4423	0243 - 0248.	
V39A RAF 4396	0150 - 0157.	
1978		Scale 1:20,000
78/22	794, 817.	
78/23	992 - 998.	
78/24	390 - 397.	
1979		Scale 1:20,000
79.5	124 - 159.	

DRAFT OUTLINE OF A STUDY OF THE IMPACTS OF CURRENT AND PROPOSED CORAL SAND DREDGING IN THE SUVA AREA.

A number of the anticipated social and environmental impacts (positive and negative) of the proposed dredging will be studied and reported upon. Whenever possible, firm management proposals designed to alleviate negative impacts and to strengthen positive impacts must be developed from the results of the study.

Whereas the social and environmental impacts will be the main concern of the study a brief review is required of the company's role in the national economy and the significance of the coral sand deposits for the company's development.

If, after consideration of the completed study, a foreshore lease or leases is to be granted then monitoring of appropriate social and environmental parametres will be required for a period after the initiation of dredging. Bearing this in mind, such benchmarks must be established and benchmark data collected during the study as will facilitate the monitoring programme.

Though all aspects of the proposed study are interrelated, for convenience the study outline is broken down into three components.

Resource Economics
Social Impacts
Environmental Impacts

RESOURCES ECONOMICS:

A brief report is required on the industry's past and expected future role in the national economy, particularly in terms of the industry's contribution to foreign exchange earnings and local employment. Special consideration should be given to the possibly heavy demands likely from the Nadrau Hydro-electricity scheme and the Namosi copper prospect.

The report should include details of:

Percentage ownership by Fiji citizens, directly and indirectly.
Employment data.
Materials, supplies energy and water purchased for production.
Transport , Repairs and maintenance expenses.
Production and Sales.
Assets.
Future Capital Investment Programme
Utilization of Capacity.

Further, estimates of the extent of the reserves of coral sand in the current licence areas at Laucala Bay and in the proposed Namuka lease area, are required. These estimates must be prepared on the basis of procedures acceptable to the Director. Division of Mineral Resources.

ENVIRONMENTAL IMPACTS:

The major environmental impacts are expected to be those occasioned by:

1) fine sediments disturbed during dredging;
2) changes in water circulation and patterns of sedimentation resulting from removal of coral sand and the blasting of passages; and
3) changes in the marine food resource base resulting from substrate modifications.

1. Sediment Disturbance

The area affected by suspended sediment in the laucala Bay licence area should be defined, the biological communities in that area described and the effects of sediment under various weather conditions explained. Some quantification of suspended sediments, their rates of settling and their interception of solar energy will be required and the reactions of selected marine organisms to these settling sediments should be studied. Such measurements must be accompanied by related physical measurements (such as wind, currents, water temperatures ans salinity) paying particular attention to the frequent occurrence in the area of a surface layer of low salinity water.

Attention should be paid to the possible occurrence of an anaerobic, toxic sediment layer which, being disturbed, may be damaging to certain marine organisms.

Data and understanding derived from investigations at Laucala Bay and from appropriate observations (e.g. of coral response to the removal of sedimentation stress) made in the now unused lease area at Lami should be used as basis for predicting the extent and nature of sedimentation effects in the Namuka Island area.

Permanent quadrates should be established where appropriate and be so marked and their locations so described on plans as to make it possible for these to be used in future research. Quadrat shapes and sizes must be chosen so as to be compatible with a national system of marine benchmarks now being established.

From the results of these studies predictions will be made of the nature and degree of the sediment impact on existing biological communities, with particular reference to m rine food specis. Appropriate means of hastening the recovery of seagrass and coral communities should be investigated and re-habilitation proposals made.

2. Bathymetric Changes.

The removal of coral sand and the blasting of boat passages will alter water circulation and cause shifts in the relationships between sediment sources and sinks. One possible consequence is the depletion of shoreward sediments to an extent which may make the shore more vulnerable to erosion.

A study is required of the sediment budget in the Namuka Island area (and relates to the study of sand reserves) From this study predictions should be made of the extent and nature of changes in this budget and the consequences for reef, lagoon and shore geomorphology.

Particular attention should be paid to different techniques for coral sand dredging, e.g. the dredging of continuous channels in sand deposits as compared with the present practice of isolated deep holes. This aspect of the study also is of biological significance and should be so reported.

The extent of water mixing (turnover times) should be calculated for predredging and post-dredging situations.

3. Substrate Changes.

Changes in substrate as a consequence of dredging will mean changes in associated biological communities. There may be a depletion of certain communities or a complete loss. Where marine food species are involved some quantifications of the effect is required. Where other species, of indirect significance to marine food species, are identified, a descriptive account of effects should be prepared.

Where post-dredging recovery can be expected estimates should be made of recovery rates.

SOCIAL IMPACTS:

It will be necessary to investigate the nature and extent of the subsistence and commercial dependence of the villagers of Muaivuso, Nabaka and Waiqanake on marine foods in the area which would be expected to be affected by sand-dredging in the vicinity of Namuka Island. The information and understanding so obtained will be used as a basis for predicting the social impact of any dredging project on these village communities.

Any positive impacts (e.g. improved employment opportunities) should also be considered.

Consideration should be given to any modifications of dredging techniques which can be devised to minimize adverse social impacts resulting from disturbance to marine food resources.

The divisional Commissioner (Central) should be consulted regarding arrangements for the study of social impacts.

UNIVERSITY OF THE SOUTH PACIFIC

INSTITUTE OF NATURAL RESOURCES

DRAFT ONLY

A STUDY OF THE IMPACTS OF THE CURRENT AND PROPOSED CORAL SAND DREDGING IN THE SUVA AREA.

1. INTRODUCTION

1.1 With reference to the draft outline of the above study from the Environmental Adviser to the Fiji Government, attention has been focused upon those aspects necessary to initiate the study so as to ensure the maximum utilization of resources with the minimal environmental impact. Discussions have been held with interested parties within Fiji. Unfortunately, in preparing this informal draft it has not been possible tc discuss the suggestions with the Environmental adviser. Further discussions are recommended prior to drawing up the detailed study plan.

2. ESTIMATION OF CORAL SAND RESOURCES

2.1 Equipment is presently available within Fiji to chart the upper geological layering within the lagoon areas. It is proposed that this study receive input from both Fiji Industries and the Geological section of the Department of Mineral Resources. The suggested contribution from Fiji Industries is as follows:

2.2 FIELD WORK

Areas accessible to the Lami site could be covered in ten working days, including preparation time. During this time, support is required for the following:

(a) Professional Geologist

(b) Assistant

(3) Boat and Boat Crew

2.3 INTERPRETATION OF THE DATA

Information relevant to resources of coral sand would be obtained within twenty man days by a Professor Geologist. An assistant for the same period is required to assist in drawing up maps.

2.4 MAPPING MATERIAL:

Material for the production and duplication of maps is required.

2.5. CHEMICAL ANALYSIS

Five man days for analysis of representative samples.

3. REQUIREMENTS FOR CORAL SAND

3.3 Utilization of the resource to maximize the economic return and minimize the environmental impact requires estimates of the demand for coral sand. Possible future developments such as the Nadrau Hydro-Electric scheme and the Namosi copper project should be included in this study. The feasibility of the possible substitutes for coral sand should also be investigated. To obtain a meaningful conclusion from this section will require a minimum allocation of twenty man days from a professional analyst.

4. BASELINE ENVIRONMENTAL DATA

4.1. The environmental impact can only be gauged with reference to ecological standands. The establishment of permanent quadrants for this purpose requires priority. Such a system should be compatible with a Fiji National system of benchmarks now being established. The thorough investigation of a limited number of carefully selected quadrants is suggested for this study. Quadrants should include now unused areas from which coral sand had been extracted, likely extraction sites and reference quadrants not within proposed lease areas. In addition to documenting the biological species within the selected quadrants, the physical and chemical nature of the sediments should be defined. A minimum of fifty man days is estimated for this section of the investigation.

4.2. Bulk physical data should be documented for the lease area. Measurement required would include wind, currents, water temperature, salinity and suspended solids. Ten man days is required to outline this information, making maximum use of information presently available.

5. LONGER TERM STUDIES

5.1. It is suggested that the studies as outlined above should be started as soon as practical. Within the findings of sections 2 and 3, a tentative coral sand mining schedule would allow a more concentrated investigation of the factors associated with the operation.

6. BATHYMETRIC CHANGES

6.7 Investigation of the sediment balance for the area will enable the effect of the removal of coral sand and the formation of boat passages to be investigated. Effects may range from zero if sand is being lost to deeper water to an increase in shore erosion if current patterns are changed by the dredging. The effect of various sand dredging procedure upon sand and water movement should form part of this study. Foutty professional man days utilized over a period of at least twelve months is the minimum which will provide meaningful results from this section of the investigation.

7. BIOLOGICAL VARIATIONS.

7.1 Variation of sediment and water patterns will cause variations in associated biological communities. Physical interactions arise from the variation of suspended sediments, solar radiations and physical deposition of sediments. Biological interaction may be developed through the food chain. Much of this investigation forms part of that in section 4.1. Information obtained as part of studies outlined in sections 4.1 and 6.1. is used to predict possible changes in the biological communities. This work is most appropriately done a in the first instance by the professionals engaged in section 4.1. Initial predictions should be periodically monitored with refence to the long term investigation of the biological communities within the defined quadrants of section 4.1. Twenty professional man days is allocated for drawing up the initial postulated variation of biological communities. To maintain the quadrant registrar sixty man days per annum should be allocated.

8. SOCIAL IMPACTS.

8.1. Changes in biological food chains in the area has the potential to vary the amount of sea food used for human comsumption. Information is required of the amount of marine food presently obtained in the study area. Ten man days is required for this study. Extrapolation of information from section 7.1 will enable prediction of possible variation of the species presently contributing on a commercial or subsistence basis.

8.2. The use of water channels by residents of the area for transport should be documented. Variation of the patterns of water movement may affect established habits. Five man days will enable this aspect to be surveyed.

8.3. Other social interactions arise from the presence of the dredges and barge traffic in the area. Employment opportunities may be created within the employment policy of Fiji Industries. The importance of the water area to tradition customs and beliefs may be considered. Ten man days will enable the documentation of these aspects.

9. RESOURCES ECONOMICS

9.1. Environmental decisions made with the reference to the economics of the cement industry and its contribution to the Fiji economy will ensure the stability of industry and the feasibility of the decisions. This investigation is an extension of that outlined in Section 3. The suggestion made by the Environmental adviser to the Fiji Government for the study all form part of management planning for the cement industry. Direct advise is required from the industry prior to further details being considered for this section.

APPENDIX III.

SYRINGODIUM ISOETIFOLIUM; INCREASE IN LEAF LENGTH, MEASURED 23-26 MARCH AND 30 MARCH - 2 APRIL, 1982. SEAGRASS TRANSPLANT EXPERIMENTS, DREDGE PIT WAIQANAKI III.

Transplant Code	Depth Below C.D. (m)	Description
TB1	1	Suspended transplant box.
TB3	3	Suspended transplant box.
TB5	5	Suspended transplant box.
TB7	7	Suspended transplant box.
TB9	9	Transplant box in dredge pit floor.
TBControl	1	Transplant box in donor seagrass bed.
SB9	9	Transplants in dredge pit floor.
Control	1	Undisturbed area of donor seagrass bed.
Cage R	7.5	Transplant, caged, by artificial reef.
Cage O	7.5	Transplant, caged, in open area.

I = increase in leaf length.

L_{obs} = length at time of measurement (T_1), mm.

TIP (P) = leaf tip intact.

TIP (A) = leaf tip absent.

Obsn. Period = duration of experiment, $T_1 - T_o$, light days.

T.C. = Transplant Code.

O.P. = Observation Period.

APPENDIX III - DREDGE PIT WAIQANAKI III. 23-26 MARCH, 1982.

T.C.	TB 1		TB 3			TB 5			TB 7			TB 9			TBControl			SB 9			Control		
O.P.	2.9		2.9			2.8			3.0			3.1			2.9			3.0			2.9		
I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP
29	56	P	11	130	P	19	83	P	22	74	P	23	70	P	24	180	A	22	46	A	27	222	A
26	46	P	28	161	P	18	121	P	15	63	A	25	73	P	12	85	P	25	103	P	27	174	A
23	181	A	30	71	P	21	38	P	22	39	A	24	91	A	17	79	P	19	156	A	25	36	P
10	122	A	25	69	P	17	105	P	15	85	A	17	82	A	20	124	P	9	73	P	26	150	A
25	69	P	27	122	P	13	75	A	14	37	A	13	90	A	15	126	A	10	131	A	20	59	P
24	115	P	23	128	P	7	44	P	17	115	A	15	80	A	22	186	A	16	50	P	20	119	P
16	39	P	23	136	A	12	114	P	21	80	P	23	85	P	17	81	P	14	63	P	31	63	P
25	126	P	32	66	P	15	160	P	20	91	A	19	57	P	17	200	A	20	127	P	21	140	A
24	117	P	19	26	P	7	69	P	20	100	A	21	38	P	9	42	P	27	53	P	22	137	P
26	90	A	26	68	P	4	5	A	10	45	P	19	69	A				9	124	P	27	156	P
13	46	P	25	84	P	7	44	P	19	42	P	21	124	A				13	130	P	20	121	P
25	110	P	25	61	P	14	112	P	15	102	A	15	53	P				10	11	P	28	179	P
19	30	P	24	76	P	9	82	A	16	73	A	26	46	P				9	156	A	29	119	P
12	69	P	23	116	P	19	217	A	23	56	A	13	104	A				15	34	P	30	74	P
21	110	A	26	71	A	15	163	A	21	60	A	21	73	A				24	181	A	21	143	P
20	90	A	25	87	P	17	59	P	22	74	P	10	17	P				15	231	A	25	84	P
			20	143	P	22	83	P	11	43	P	5	63	A				16	167	A	28	141	P
			27	132	P	10	100	A	17	79	A	13	143	A							17	55	P
			27	90	P				6	51	P	18	33	P							32	105	P
			21	34	P				19	41	A										26	65	P
									13	44	P												
									15	37	A												
									24	54	P												
									25	64	P												

APPENDIX III - DREDGE PIT WAIQANAKI III. 30 MARCH - 2 APRIL, 1982.

T.C.	TB 1		TB 3			TB 5			TB 7			TB 9			TBControl			SB 9			Control			Cages		
O.P.	2.7		2.7			2.7			2.7			2.8			2.7			2.8			2.7			2.8		
I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP	I	L_{obs}	TIP
14	91	P	22	159	P	22	38	A	17	31	A	11	15	A	21	79	P	17	32	P	16	89	A		R	
10	56	P	27	51	A	15	22	A	18	27	A	15	16	A	14	82	P	19	94	P	23	92	P	14	56	P
23	73	P	31	138	P	3	16	A	11	16	P	3	4	A	12	37	P	15	76	A	20	88	P	19	123	A
16	41	P	5	37	A	14	73	P	19	34	P	8	11	A	21	90	P	2	2	A	27	96	P	23	177	P
29	112	P	6	75	P	12	21	P	9	17	A	12	13	A	17	112	P	22	70	P	31	73	P	23	63	P
28	114	P	20	66	P	15	46	A	7	18	A	13	16	A	18	92	A	14	37	P	19	149	A	19	239	A
21	25	A	17	27	A	15	38	P	14	19	A	18	21	A	18	31	P	15	27	A	28	56	P	10	60	P
26	129	P	13	38	A	21	83	P	14	15	A	20	26	A	11	96	P	18	43	P	25	82	P	28	80	P
15	56	P				18	48	P	10	11	A	14	19	A	18	47	P	20	30	P	22	116	P			
26	81	P				7	9	A	8	10	A	7	9	A	6	62	P	14	45	A	24	109	A		O	
20	103	P				5	36	P	11	17	A				20	35	P	19	48	A	14	94	A	18	145	A
20	79	P				19	149	A							23	64	P	19	30	A	34	50	P	15	62	A
22	51	A													20	59	A	22	32	A	20	70	P	13	37	P
21	84	P													18	68	P				28	130	P	24	115	P
18	74	P													12	83	A				26	78	P	20	56	P
22	57	P																			26	87	P	23	78	P
28	102	P																			27	100	P	30	71	P
																								17	50	P
																								14	47	A

Note: T.C. = Transplant Code.

O.P. = Observation Period.

APPENDIX IV. FLORAL AND FAUNAL SPECIES LIST.

3.2.1.

Syringodium isoetifolium (Aschers.) Dandy

Halodule pinifolia (Miki) den Hartog.

Halodule uninervis (Forssk.) Aschers.

Halophila minor (Zoll.) den Hartog.

3.2.3.1.

Synodus englemani

Synodus variegatus (Lacepede).

Bothus pantherinus (Ruppell).

Apogon exostigma (Jordan & Starks).

Scolopsis cancellatus (Cuvier & Valenciennes).

Lethrinus harak (Forskal).

Lethrinus mahsena (Forskal).

Lethrinus rubrioperculatus

Mulloidichthys vanicolensis (Cuvier & Valenciennes).

Parupeneus barberinoides (Bleeker).

Parupeneus barberinus (Lacepede).

Amblyglyphidodon curacao (Bloch).

Cheilinus bimaculatus (Cuvier & Valenciennes).

Novaculichthys macrolepidotus (Bloch).

Chelio inermis (Forskal).

Thalassoma trimaculatus

Halichoeres trimaculatus (Griffith).

Calotomus spinidens (Quoy & Gaimard).

Parapercis cylindrica (Bloch).

Parapercis cephalopunctatus (Seale).

Siganus canaliculatus (Mungo Park).

Plectropomus leopardus

Gambierdiscus toxicus

Pocillopora damicornis (Pallas).

Plerogyra sinuosa (Dana).