RECENT AND MIOCENE CARBONATE SEDIMENTS FROM INDONESIA

(IN TWO VOLUMES)

BY

PENELOPE JANE LOOPUYT-TURNER

Submitted for the degree of
Doctor of Philosophy
to
Aston University
Department of Geological Sciences

March 1986

VOLUME I

ASTON UNIVERSITY

RECENT AND MIOCENE CARBONATE SEDIMENTS FROM INDONESIA

by

Penelope Jane Loopuyt-Turner

Submitted for the degree of
Doctor of Philosophy
at Aston University
March 1986

Summary

Mapping and sediment sampling in reefs of the Pulau Seribu group (southwest Java Sea) shows the existence of ten physiographic zones and subzones represented by seven lithofacies. Reefs in the northern part of the archipelago are smaller, more closely spaced and morphologically simpler than those in the south. This pattern is attributed to differences in subsidence rate. A three-dimensional model is proposed for the evolution of these reefs but borehole data are required to test this model.

Miocene limestones are described in detail from hydrocarbon reservoirs in the Batu Raja Formation of the same area. Brief comparisons are made with surface outcrops of approximately coeval carbonate developments. The lithofacies developed within these limestones reflect variations in hydrodynamic regime and basement topography. Eleven diagenetic processes affected the Batu Raja limestones and the distribution of these is primarily related to sealevel fluctuations. Early diagenesis was marine and characterised by micritisation and precipitation of fibrous and bladed cements. Dolomitisation occurred in the mixed-water zone and its variable intensity is attributed to the configuration of the carbonate body relative to this zone. Subsequently the limestones were subjected to freshwater phreatic zone diagenesis resulting in dissolution and cementation, and at a late stage underwent burial compaction. Secondary porosity, which largely determines the suitability of these limestones as hydrocarbon reservoirs, is a function of the variable intensity of dissolution and cementation, burial compaction, dolomitisation and possibly micrite neomorphism.

The sedimentary processes that generated the Batu Raja buildups are inferred from comparisons with the Pulau Seribu and other Recent analogues. The contrasting pinnacle form of the Pulau Seribu patch reefs compared with the low relief of the Batu Raja buildups results from differences in the initial substrate topography and subsequent subsidence rate.

Keywords

Recent, Miocene, Indonesia, Carbonate, Diagenesis

LIST OF CONTENTS

Page

Page

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION METHODS AND MATERIALS

1.1 INTRODUCTION AND OBJECTIVES

The primary aim of the thesis is an appraisal of Recent environments of carbonate sedimentation in the south-west Java Sea, Indonesia, and the proposal of a sedimentological model for the area, in order that this might assist in the interpretation of Miocene reefal buildups from the same area. The project developed as a result of the considerable importance of these buildups as hydrocarbon reservoirs (Leslie 1976; Beddoes 1980; Fletcher & Soeparjadi 1982). Because of the complex active tectonic regime in which the Miocene buildups developed (Fig. 1), and because of their relative isolation from the open ocean, it is difficult to draw close analogies between them and the classic areas of reef study such as the Great Barrier Reef, Bahama Bank and Florida Keys. The proximity between the Recent and Miocene sites of carbonate sedimentation studied however, and the similarity in their tectonic setting, invites comparison between the two.

The varying usage of terms such as ecologic, stratigraphic or organic reef, buildup, bioherm, biostrome and mound in the literature, has caused confusion and ambiguity (Dunham 1970; Braithwaite 1973). In this thesis, the term "reef" is used in the narrow sense of Lowenstam (1950) as refined by Braithwaite (1973). A reef has the following four qualifying attributes; wave resistance, a high proportion of frame builders, significant relief above the seafloor within the zone of wave action and finally, a zonation which is created and perpetuated by this self-generated relief. The term "carbonate buildup" is used to refer to a laterally restricted body formed of carbonate sediment which has topographic

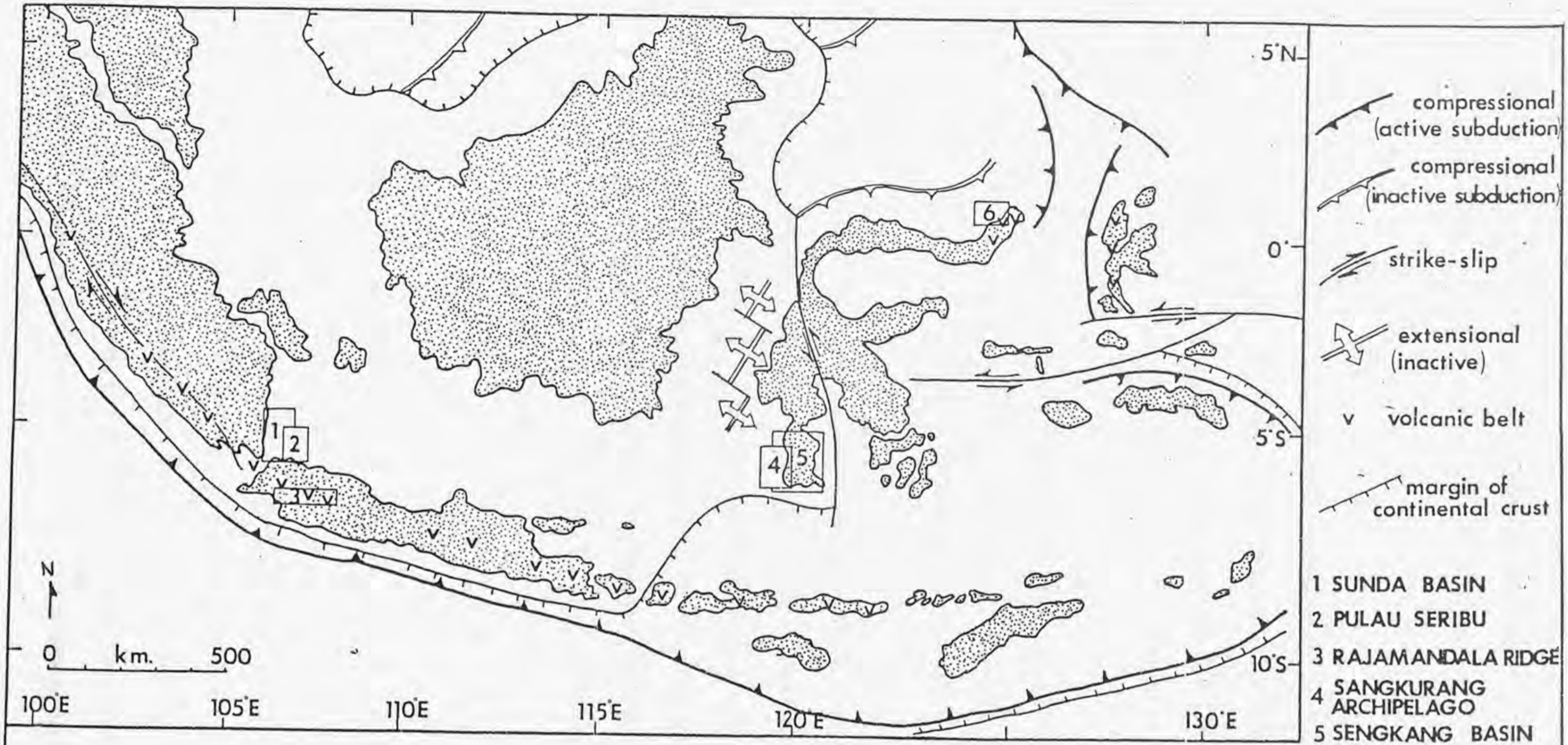


Figure 1 Index map of Indonesia showing study areas and major tectonic elements.

relief. Such a definition encompasses the reef as defined above, but buildup is used where insufficient framework is preserved to be sure that the structure was wave resistant.

In the study of Recent reefs, attention was focussed on the Pulau Seribu (Thousand Islands) reefs in the south-west Java Sea, although brief visits were also made to the Sangkurang Archipelago in South Sulawesi and the reefs west of Manado in North Sulawesi. In assessing growth and development of Recent reefs, three main aspects are involved:

(a) The identification of, and description of variation in, Recent sedimentary environments and the recognition of a number of distinct facies. The criteria by which facies are identified are discussed in Section 2.6.1.

(b) Consideration of the evolutionary development of the Recent reefs through progressive stages to maturity. A three-dimensional model is presented illustrating the manner in which facies arrangement and geometry is modified from an incipient reef to a mature reef complex.

(c) An appreciation of external controls on reef growth such as terriginous sediment and tectonic control, and consideration of these influences on different types of Indonesian reefs.

Vertical and near-vertical cores from wells through the Lower Cibulaken Batu Raja Limestones (Early Miocene) were logged, and fieldwork was undertaken on the Rajamandala Limestones (Early Miocene) of west Java, Sengkang Basin Limestones (Eocene-Late Miocene) of South Sulawesi, and Parigi Limestones (Middle Miocene) of west Java. The characteristics and evolution of the Miocene Batu Raja buildups were also examined on a three-fold basis:

(a) Study of important sediment-producing organisms and depositional facies based on visible characteristics from core logging and petrography. A lithofacies statigraphy of the buildups was established and facies sequences were used to infer the primary controls on carbonate deposition.

(b) Study of diagenesis and the distribution of diagenetic products.

(c) Study of the contrasts in the character of carbonate deposition between buildups developed in the Batu Raja Limestone and other fossilised Indonesian examples.

Chapter 1 covers general topics including sample collection and preparation. The remainder of the thesis is organised into three sections. Chapter 2 concentrates on Recent reefs and involves description and analysis of field data gathered from surface observations only. The three-dimensional model (Section 2.7) is inferential and involves ideas on the evolution of a single reef within the Pulau Seribu, and of the Pulau Seribu as a whole. Chapters 3-4 compare material from outcrops and subsurface Early Miocene buildups, and a picture is built up of the controls affecting Miocene sedimentation and subsequent diagenesis. Chapter 5 integrates the conclusions of Chapter 2 and Chapters 3-4 resulting in a comparison of Recent and Miocene sedimentary environments.

1.2 ACKNOWLEDGEMENTS

I thank Drs. A. T. Thomas and P. Turner for supervising the project and Professor D. D. Hawkes for the provision of facilities. The following kindly contributed information and material: Drs. A. Haslett and S. Prior (Atlantic Richfield Company, Jakarta); Drs. D. Beard, A. Wight and Handoko (Independent Indonesian-American Petroleum Company, Jakarta); Dr. R. Koesoemadinata (Institute of Technology, Bandung); Dr. R. Wharton (Mobil Oil, Jakarta) and Mr. R. Cook (P.T. Bessindo, Jakarta). Logistical support was provided by Ms. G.

Tidey, Dr. D. Harrison and Tini Sudendar (Lemigas Biostratigraphical Services Unit, Jakarta); P. T. Lemigas, Jakarta; Dr. S. Schuleman (British Petroleum, Jakarta) and Lembaga Oseanologi Nasional (L.O.N.-L.I.P.I.), Jakarta. Lembaga Ilmu Pengetahuan Indonesia (Indonesian Insitute of Sciences) gave formal approval for the project. Financial support from the Robertson Research group and the Natural Environmental Research Group is gratefully acknowledged. Mrs. H. Turner patiently typed the manuscript.

1.3 RATIONALE BEHIND SITE-SELECTION IN THE PULAU SERIBU, AND COLLECTION OF RECENT SAMPLES

Selection of specific sites for investigation was carried out with the aid of aerial photographs and maps (Oceanographic chart 2056 1956, revisions 1980; Netherlands Government Survey charts, Thousand Islands Northern and Southern parts 1885-86). The sites were chosen so as to provide as representative an idea of the sedimentary environment as possible. Fieldwork was part boat-based and part island-based.

The patch reefs were systematically examined by snorkel and SCUBA diving to a depth of 35m. and sediment was collected from each identified sedimentary environment and subenvironment (Appendix 1). A sedimentary environment or subenvironment is a restricted area within which sediment is deposited under essentially the same conditions. 100-200 gm. of sediment were removed by hand and scooped into a polythene bag which was sealed underwater. The number of samples taken per unit was dependent upon the sediment area proportional that of the reef as a whole and variability within the sedimentary unit.

Underwater photographs were taken with a Nikonas III camera made available by Robertson Research Limited, using Kodachrome 64 film.

Samples prefixed PSM, most of which are from deep inter-reef channels, were collected during 1983-84 by Mobil Oil as part of an independent Mobil Oil project. A remote grab sampler attached to a winch on board a boat was used to recover these samples.

1.4 SAMPLE TREATMENT

1.4.1 Recent Unconsolidated Samples

Two hundred unconsolidated sediment samples were collected from the Recent reefal environments. Sediment was stored wet in sealed plastic bags. After 12 hours drying at $40^{\circ}C$, approximately 100 gm. of sediment from each sample was separated, disaggregated by gentle crushing using a pestle and mortar, and seived for 15 minutes on a Ro-Tap machine using a 0.5ϕ interval. Class names proposed by Wentworth (1922) and the logarithmic grain size scale devised by Krumbein (1934) were adopted in calculation of the weight percents for gravel, sand and mud. Quantitative determination of the percentage frequency of various skeletal grains constituting samples from different environments was accomplished by point-counting. Four grain size fractions of each sample were selected, representing fine, medium, coarse and very coarse sand. Each fraction was impregnated with araldite resin, thin-sectioned and stained with combined stain (Dickson 1965) and from each section 500 points were counted. This was undertaken in order that compositional differences between different grain size groups were determined in addition to identifying variability between sample localities (Section 2.6.2).

The mud fraction of selected samples was examined by x-ray diffraction to determine the mineralogy and hence infer probable genesis. The insoluble terriginous fraction which, in most samples constituted a minor proportion of the total mud percent, was isolated by dissolving selected samples in 5% HCl and separately x-raying the residue.

1.4.2 Recent Coral and Mollusc Samples

Samples of both living and dead corals and molluscs were collected in order to study the variability and nature of bioerosion and cementation on the reef slope and reef flat. The samples were slabbed using a rotary saw, and examined with a hand lens. Selected samples were thin-sectioned for more detailed examination under a microscope.

1.5 SAMPLE TREATMENT; MIOCENE CORES AND OUTCROPS SELECTION OF MATERIAL

Miocene samples from fourteen wells, and outcrop samples were used in the study. The wells came from three hydrocarbon reservoirs; the Duma, Nurbanic and Zu (=Bima) reservoirs from the south-west Java Sea. Work on the offshore reservoirs involved conventional logging of vertical and subvertical cores. Core logging and sampling was undertaken in the offices of IIAPCO and P. T. Lemigas in Jakarta.

The wells penetrate the entire Plio-Pleistocene, Upper, Middle and most of the Early Miocene. The cored interval varies from 9-75 m. and is restricted to the Batu Raja and Gumai formations. A list of core samples used is presented in Appendix 2. Conventional 12 cm. diameter slabbed cores were logged. Slabbing was done by P.T. Seta Yasa Ltd., Jakarta, Indonesia. Due to the nature and quality of the cored material from the Nurbani-10 and ZZZ-2 wells, these cores were not slabbed and consequently difficulties were experienced in the subdivision of lithologies. Results are presented in the Carbonate Core Summary Charts in Appendix 4. The charts were devised based on a modified version of standard charts used by Robertson Research Int. Ltd.

The notation of sample numbers incorporates the field, well number and depth e.g. N41737' refers to a sample from the Nurbani-4 well from a depth of 1737 feet. Drilled depths are quoted in feet to preserve consistency with electric log charts and drilling depths used by the oil companies concerned and, except in the case of sample numbers, equivalent depth in metres is quoted in brackets. In Chapter 2, which concerns Recent carbonates, all distances are metric.

The lithological and palaeontological symbols used in this thesis are a blend of the Robertson Research standard legend and my own ideas (see Appendix 3 for explanation). The Embry & Klovan (1971, Fig. 2a) classification of limestone textures, and the Archie (1952, Fig. 2b) and Choquette & Pray (1970) classifications of porosity were adopted. Use of the Embry & Klovan classification permits a rapid and meaningful assessment of texture and relates well to environment of deposition. With a 1:180 vertical scale, lithologies less than 1' (30 cm.) thick are not represented in the lithology column. However, thin but significant bands are recorded in the comments section.

1.6 LABORATORY ANALYSIS

Facies analysis was carried out incorporating lithological relationships, field observations, results from core analysis, microfacies and diagenetic information from petrological studies. Rather than carry out a detailed palaeontological study, general palaeoecological observations were used to relate

Fig.2a TEXTURAL CLASSIFICATION OF EMBRY & KLOVAN 1971

ALLOCHTHONOUS: Original components not organically bound during deposition						AUTOCHTHONOUS: Original components organically bound during deposition		
>10% components > 2mm				>10% grains >2mm		By organisms which act as baffles	By organisms which encrust and bind	By organisms which build a rigid framework
Mud supported		Matrix supported		Matrix Supported	Supported by 2mm components			
less than 10% grains	Greater than 10% grains		No lime mud					
MUD~STONE	WACKE~STONE	PACK~STONE	GRAIN~STONE	FLOAT~STONE	RUD~STONE	BAFFLE~STONE	BIND~STONE	FRAME~STONE

Fig.2b ARCHIE CLASSIFICATION OF POROSITY (1952)
(Modified by Robertson Research Singapore Ltd)

Type	I	compact, crystalline	appearance in hand specimen
	II	chalky, dull, earthy	
	III	granular	
Class	A	none visible, <20μ	visible pore size
	B	20—125μm	
	C	125μm-2mm	
	D	<2mm	
Interconnection	c	connected pores	
	d	disconnected pores	
Crystal Size	very fine	50μm	
	fine	100μm	
	medium	200μm	
	coarse	400μm	
Description	good	>10	% of surface covered by visible pores
	fair	5-10	
	poor	<5	
	absent	No pores visible	
	fractures only	F	

organic associations and sedimentary features. A systematic laboratory programme was undertaken involving the following techniques:

1.6.1 Peels

The technique followed is that described by Stewart & Taylor (1965). Peels were examined under a microscope after being mounted between glass slides. The acetate peel was also used as a negative so that photographic enlargements of structures could be taken.

1.6.2 Thin Sections

Samples collected for thin-sectioning were representative of specific limestone facies or textures. In staining of sections and peels, the technique described by Dickson (1965) was adopted. Combined stain was used to facilitate the differentiation of carbonate minerals through qualitative colour comparison, and recognition of different iron compositions. Petrographic description follows the nomenclature of Friedman (1965a).

A series of photomicrographs were taken using a Zeiss Photomicroscope II. The photographs illustrate characteristics of particular facies and specific diagenetic fabrics referred to in the text.

1.6.3 X-ray Diffraction

Selected samples of Miocene and Recent material were x-rayed using Ni-filtered CoK_α radiation on a Phillips PW 1130/40 machine. Diffractograms were analysed to determine constituents of the clay mineral assemblages, and the calcite: dolomite ratio calculated using peak heights (Section 4.4.3).

1.6.4 Cathodoluminescence

Uncovered and unstained thin sections were examined by a Technosyn Cold cathode luminescence model MK11, using a 500 mA gun current and a kV between 12 and 15. The thin sections were highly polished and cleaned with inhibisol prior to examination.

The interpretation of luminescence in the rocks studied uses the conclusions derived from the work of a number of previous workers. Stehli & Hower (1961) and Veizer (1983) gave predictions of Mn^{2+} for marine dolomites. The amount of Mn in dolomite has been correlated with the openness of the diagenetic system and intensity of alteration (Brand & Veizer 1980; Veizer 1983).

1.6.5 Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to examine details of limestone and unconsolidated sand constituents, the character of lithified lime mud and the textures of calcite cement, neomorphic spar and dolomite. The instrument used was a Cam Stereoscan 150 model. Washed sand grains from Recent unconsolidated samples and fresh fracture surfaces of Miocene samples were gold-coated in order to produce good electrical conductivity and reflectance of the electron beam. The surface to be examined was 5-10 mm. in maximum dimension and was chosen where possible exhibiting moderately homogeneous characteristics representative of the feature of interest. This minimises uncertainties introduced by the presence of multiple diagenetic textures.

CHAPTER TWO

PULAU SERIBU

2.1 INTRODUCTION AND PREVIOUS WORK

There are an estimated 15,000 to 16,000 fringing and barrier reef systems in Indonesia (de Neve 1981), together with more than 800 coral islands which occur mainly in the eastern part of the Indonesian Archipelago. A group of patch reefs in the south-west Java Sea was investigated as part of this study (Fig. 3). The Pulau Seribu (=Duizeng Islands of van Bemmelen 1949) are situated between latitutes $5^{o}25'$ - $5^{o}57'$S and longitudes $106^{o}30'$ - $106^{o}40'$E, and the reefs grow on a shallow platform 30-40 m deep (Fig. 3). In this study, particular emphasis was placed on the controls on the loci of carbonate deposition, facies distribution and the predicted subsequent diagenesis and porosity evolution.

During the inter-war period, geological and biological studies in reef physiography and coral growth were conducted in the Bay of Batavia, since renamed Jakarta Bay, by several Dutch workers including Umbgrove (1928, 1930, 1939) and Verwey (1931). The Dutch-Indonesian Snellius expedition undertook a scientific programme in the south Java Sea, offshore South Sulawesi and in the Timor Arc. This work resulted in the publication of geological and biological descriptions (Kuenen 1933). During the post-war period carbonate sedimentological studies were conducted in the Pulau Seribu by Umbgrove (1947) and van Bemmelen (1949). Over the last decade, Recent environments of carbonate sedimentation in Indonesia have become the focus of study of petroleum geologists, in order to facilitate the interpretation of ancient carbonate buildups (Scrutton 1976, 1979).

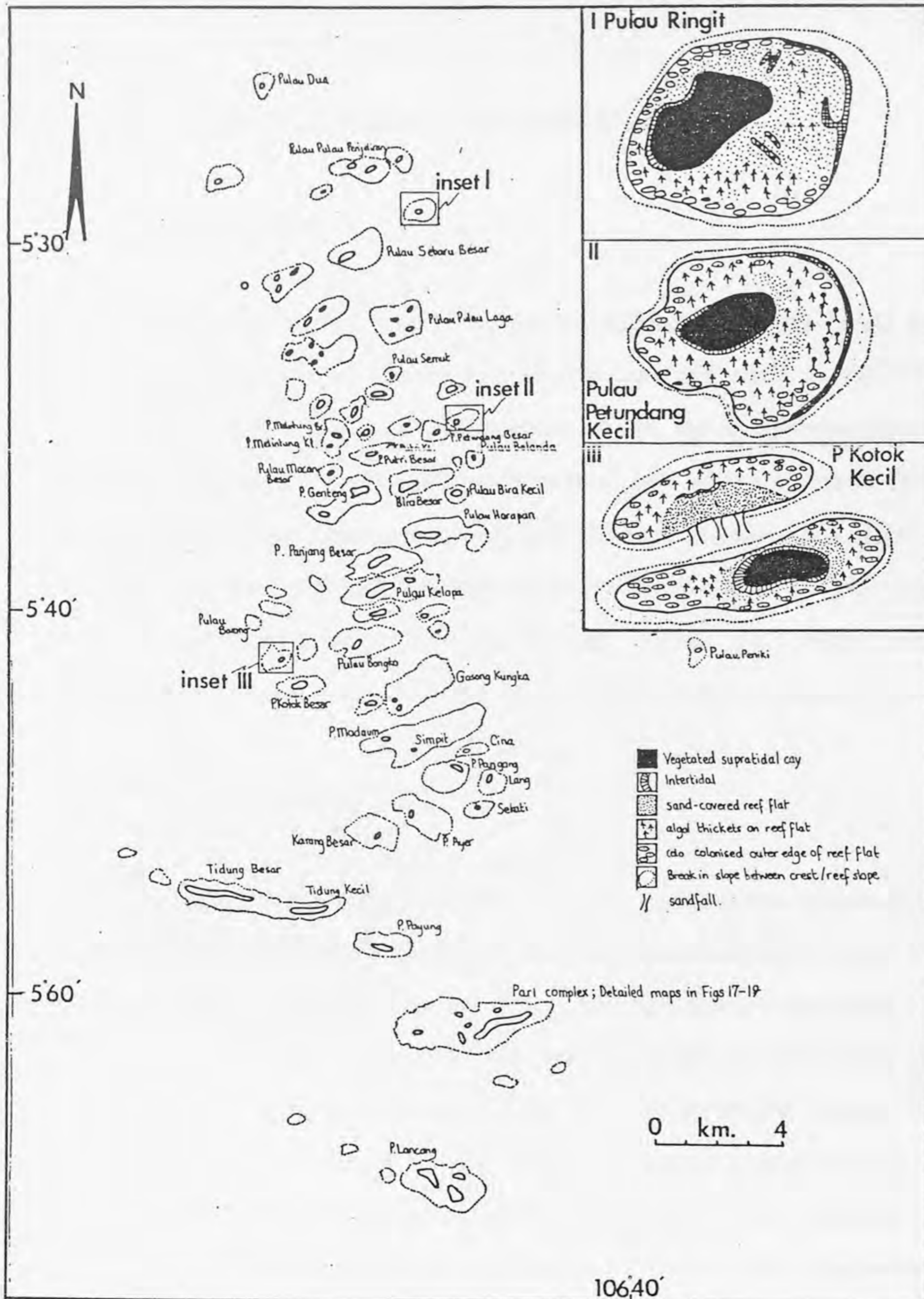


Figure 3 Map of the Pulau Seribu showing islands selected for detailed study.

2.2 GEOGRAPHIC, TECTONIC AND CLIMATIC SETTING

2.2.1 Regional Setting

The Pulau Seribu are located on the Seribu Platform in the Sunda Shelf Sea. The Sunda Shelf is the most extensive coherent shelf in the world, comprising the Gulf of Thailand, the Malaccar Straits, the south-western part of the South China Sea, Java Sea and south-western part of the Macassar Straits (van Bemmelen 1949). Contemporaneous with the Post-Pleistocene eustatic sea level rise there was epeirogenic subsidence of the Sunda shelf. Thus the Pulau Seribu may represent a better analogue to many ancient reefs which grew in epeiric seas, than those areas of modern reef study which lie on ocean margins.

2.2.2 Tectonics and Basement

The Seribu Platform is a submerged low relief plateau trending NNE-SSW for 40 km. from the coast north-west of Jakarta. The Platform is 12 km. wide and fault-bounded; to the east by the Arjuna Sub-basin and to the west by the Sunda Trough. The area within which the reefs are growing is one of the most tectonically active belts in the world (Fig. 4). The structural framework is discussed by Ben-Avraham & Emery (1973). Vertical movements of the substratum have been strong and relatively swift and this has affected reef development by influencing sea level fluctuations and relative land subsidence.

The southern part of the Platform is segmented by a submerged pre-Pleistocene drainage system. East-west orientated gorges were identified by van Bemmelen (1949). The rivers which cut these valleys deposited coarse clastic sediments which are overlain along the Java Sea margins by clayey fluvial sediments of the larger Sunda islands. The Pulau Seribu have grown up since the

FIGURE 4. MAJOR STRUCTURAL ELEMENTS, JAVA SEA AREA.
a. Sujanto & Sumatri 1977
Mercator Projection.

post-glacial sealevel rise and are therefore very young compared with other major areas of reef development such as the Great Barrier Reef (Davies 1983) and Bahaman-Florida Platform (Bathurst 1975).

The substrate in which the Pulau Seribu are rooted is unknown. With the flooding of the Platform during the post-glacial sealevel rise, sites of reef growth are likely to have been controlled by minor topographic elevations. In view of the presence of the Pleistocene drainage system, such features as fluvial levee deposits may have provided a substrate for reef initiation (Section 2.7.4). Reef growth is not continuous to the edges of the Platform although the reasons for this are unclear.

2.2.3 Climate

Since Indonesia straddles the equator, environmental conditions fluctuate very little annually, compared with the subtropical reefal areas of Australia and the Caribbean. The biannual reversal of winds and currents governed by the monsoonal climate (Fig. 5a), is instrumental in reef construction and shape (Umbgrove 1930). The alternating monsoon controls both reef growth and post-mortem redistribution of debris causing many of the Pulau Seribu islands to be elongated east-west (Plates 1, 2a, 3c, 25), orthogonal to the long axis of the underlying platform. Since neither reef flank is constantly in the lee of, or exposed to, the prevalent winds and currents, pronounced low energy and high energy rims are not formed.

Mean annual air temperature at sealevel is slightly above 26^{o}C and mean humidity measured on the Java coast is 80%. The average annual precipitation of greater than 2 m. is seasonally distributed (Fig. 5b) concentrated in the east monsoon. Rains tend to be of short duration and torrential intensity.

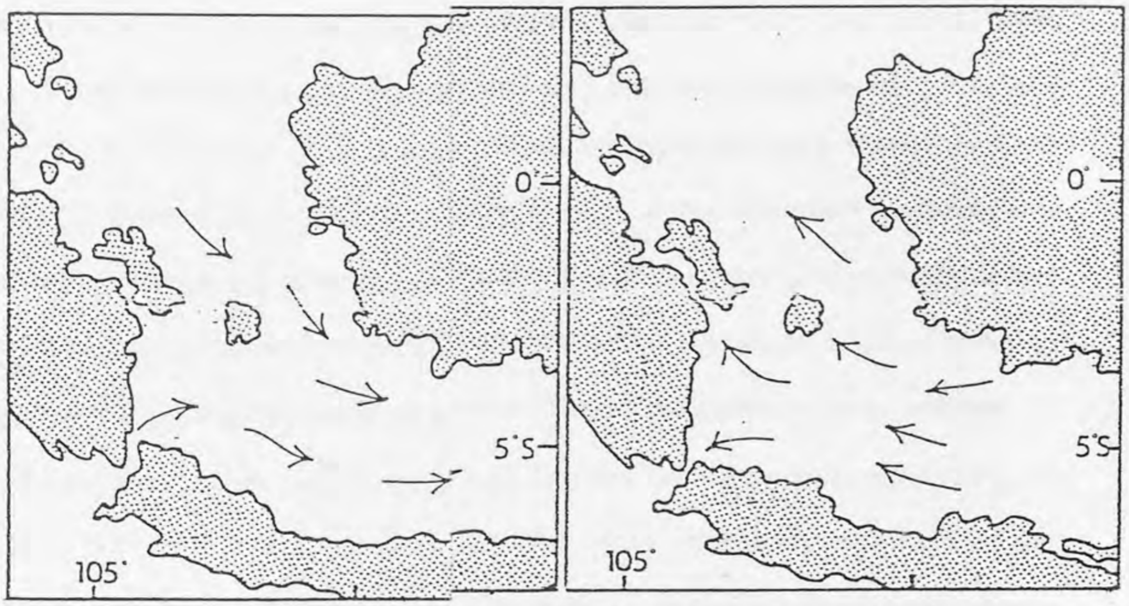


Figure 5 (a) Annual reversal of winds and currents in the West Java Sea

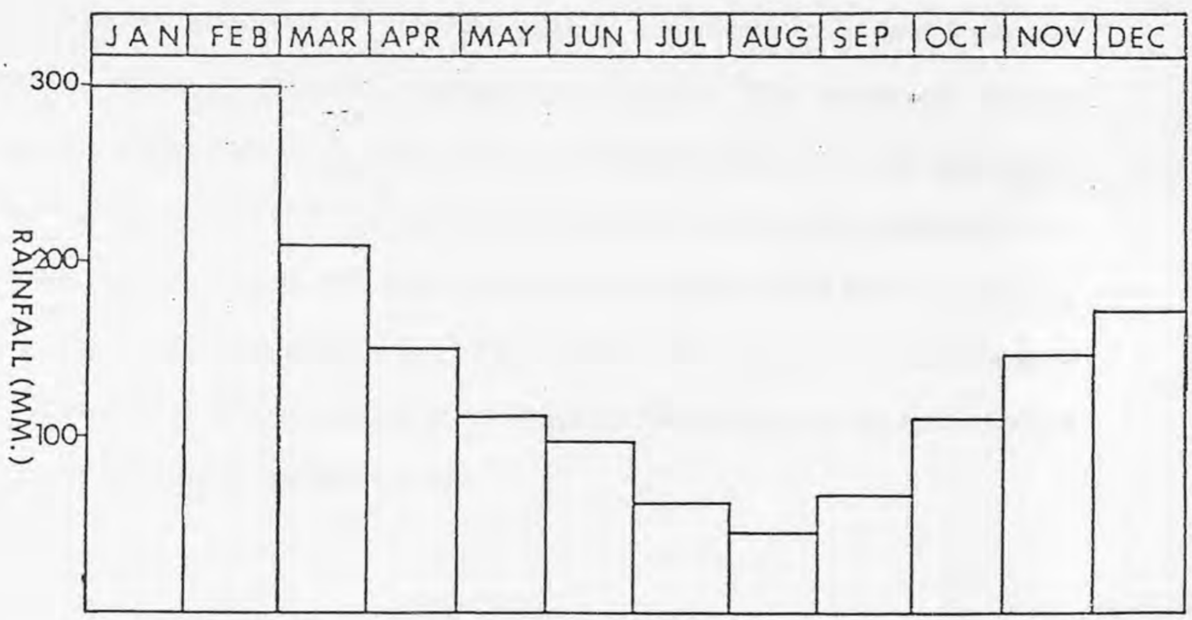


Figure 5 (b) Annual distribution of rainfall. Data from World Weather Guide 1984. Figures averaged over a 30 year period.

Surface water temperature averages 28.5°C dropping to 27.5°C at a depth of 3 m. and 26.5°C at 15 m. (Fig. 6, personal data combined with data from L.O.N.). Temperature peaks at the surface at 3 pm, but at depths of 2-4 m. the maximum is not attained until 6 pm. Minimum temperatures throughout the water column occur at 3 am. At depths exceeding 2 m., minimum temperatures are maintained for longer periods and maximums for shorter periods than at the surface. The yearly lowest temperatures throughout the water column occur in January, and the annual maximum at greater than 4 m. depth in June, between 1-3 m. in July and at the surface in October. Diurnal temperature fluctuations are greater in the east monsoon than in the west monsoon, although these fluctuations are only significant in the shallow areas of reef flats where temperatures reach 38°C.

Salinity ranges between 29-33.5°/oo, diurnal and annual fluctuations being greatest at the surface (Fig. 6). Diurnal variation in salinity approximately mimics the fluctuations in temperature, peaking between midday and 3 pm and reaching a minimum between midnight and 3 am. The maximum diurnal fluctuations occur during the east monsoon. Reef flat area is small enough to prevent the development of hypersaline or stale back-reef water masses such as have been described from the Bahamas (Bathurst 1975 p.101) and Florida Bay (Taft & Harbaugh 1964 in Bathurst 1975 p.149). The area is microtidal and is characterised by diurnal cyclicity in contrast to the more normal semi-diurnal tides of the Atlantic and Indian Oceans.

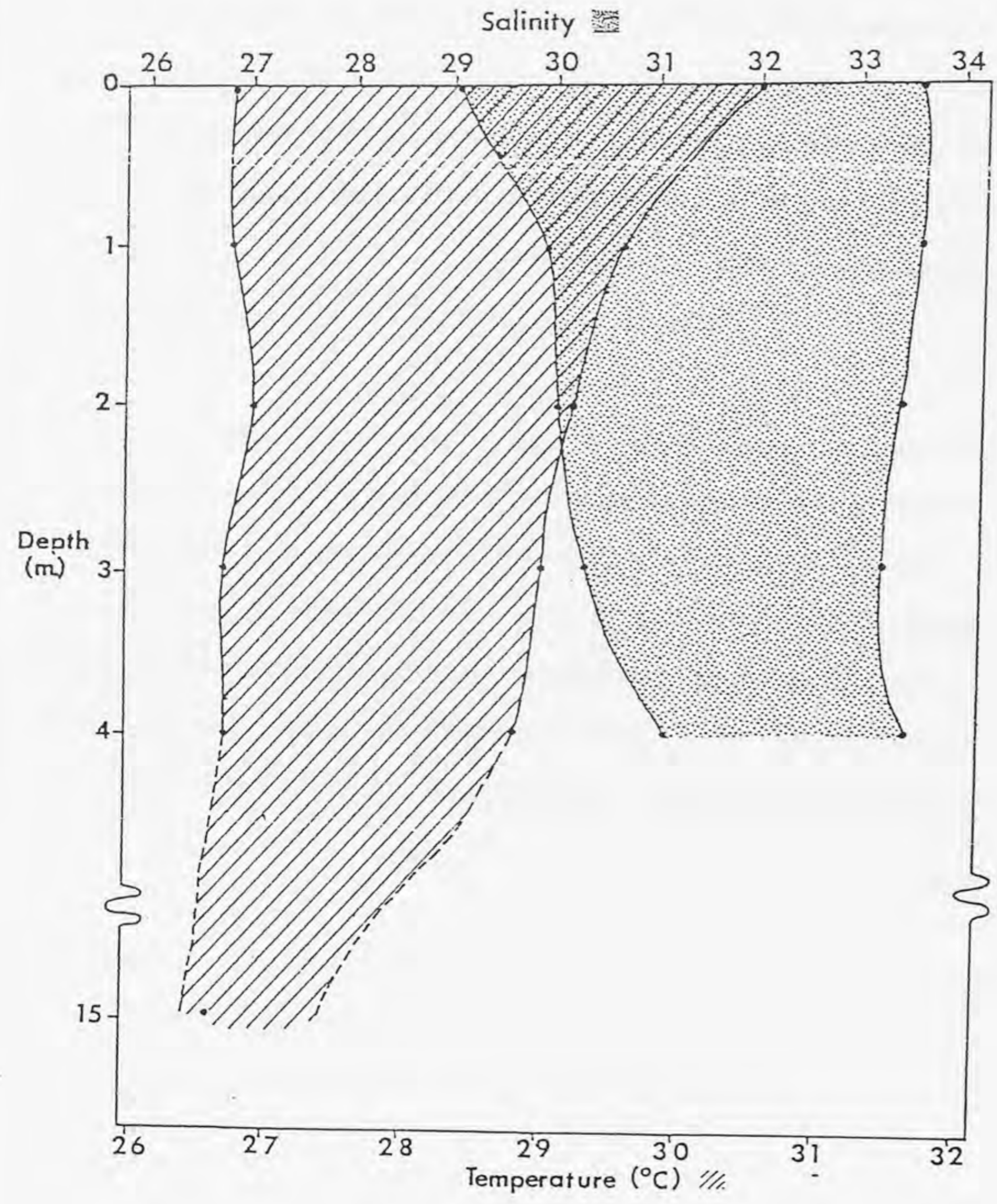


Figure 6 Salinity and temperature distribution related to depth.

2.3 REEF ANATOMY

The Pulau Seribu reefs are spaced from 35 m. to 6 km. apart and average spacing decreases northwards. Individual reefs range from 50 m. to 3 km. in maximum dimension, and ratio of reef length to width varies between one and twelve, also decreasing northwards. The reefs grow upto sealevel as they mature, and are separated from each other by channels most of which are 30-40 m. deep. The 4.8 km. wide east-west orientated Outer Channel in the southern part of the Pulau Seribu is 68 m. deep in the deepest part, and represents part of the palaeodrainage system referred to in Section 2.2.2.

The Pulau Seribu reefs exhibit a high degree of consistency in physiography and seven horizontal and vertical zones can be recognised (Plate 1). Identification of separate zones and subzones was made on the basis of water depth or elevation above sealevel, ratio of percentage in situ substrate to percentage unconsolidated sediment, the nature and diversity of faunal and floral associations, wave energy and sediment texture. Terms used to describe zones purposefully avoid direct genetic implications and are based on environmental characteristics.

Most of the islands consist of a vegetated cay surrounded by a reef flat, frequently partly enclosed within a periodically emergent coral shingle bank which borders the reef drop-off. Reefal zones identified are;

(i) sand cay

(ii) reef flat
 (a) algal flat
 (b) sand flat
 (c) outer colonised moat

(iii) lagoon

(iv) shingle rampart

(v) reef slope (a) crestal zone

(b) reef wall

(vi) reef base

(vii) channel.

These are discussed in Sections 2.3.1 - 2.3.7 and the associated lithofacies in Section 2.6.

Four islands; Pulau Pari, Pulau Kotok Kecil, Pulau Petundang Kecil and Pulau Ringit, exhibiting contrasts in size, complexity and geographical position, were selected for detailed study. Sediment sampling and identification and description of reefal zones were primarily undertaken on these islands (Fig. 31-III) although a large number of other patch reefs throughout the Pulau Seribu were also visited and sampled in lesser detail.

(a) Pulau Pari

The Pulau Pari complex is 3 km. long and 2 km. wide and is the largest patch reef in the Pulau Seribu. It comprises a complex of lagoons and cays (Plate 2a) and is located at the southern end of the Pulau Seribu chain, north of the Outer Channel. A long shingle rampart is developed on the northern and eastern rims of the reef. The northern reef slope is exposed to the strongest wave action and is shallower than the southern slope which is exposed to relatively stronger currents. The contrast in coral assemblages resulting from the contrasting hydrodynamic regimes is discussed in Brown et al. (1982).

Pari is also the name of the largest cay which is approximately 1 km. long and is located on the eastern end of the complex. This island supports mature vegetation, and a mangrove flat is developed to the north-west. The smaller islands; Tengah, Kongsi, Burung and Tikus, located on the western half of the complex, are probably considerably younger and support a more shrubby colonising type of vegetation. The lagoonal complex comprises two connected lagoons around which mangroves and new cays are establishing themselves.

(b) Pulau Kotok Kecil

Pulau Kotok Kecil, comprising two closely spaced reefs is located on the western side of the Pulau Seribu chain (Fig. 3c, Plate 2d) and is exposed to the western monsoonal storms between April and November. A vegetated cay is developed on the southern reef and to the north, the submergent patch reef supports a small periodically emergent mobile sand cay. Between the reefs is a shallow channel, 18 m. deep, through which flow strong currents upto 31 $cm.s^{-1}$. Sand falls on the southern slope of the northern reef supply sediment to this channel. The reef flat is upto 20 m. wide and unlike the Pulau Pari complex, there are no sheltered areas on the reef flat.

Vigorous coral and Halimeda growth occurs on the north-west side of the reef an less vigorous growth on the southern side of the southern reef. Coral growth is slow and patchy in the shallow inter-reef channel.

(c) Pulau Petundang Kecil

Pulau Petundang Kecil is situated on the eastern side of the Pulau Seribu chain (Fig. 3b, Plate 2c), and is exposed to the full force of the eastern monsoon, (November - March). A large rampart is developed on the eastern margin and a vegetated cay is sited asymmetrically on the western leeward side of the patch reef. Mangroves have developed on shingle bars on the outer western reef flat. A rich Halimeda zone is developed seaward of the rampart on the eastern rim of the reef. The eastern crest is wider than on most reefs, and absorbs the considerable energy of shoaling waves. Coral growth is vigorous right around the reef.

(d) Pulau Ringit

Pulau Ringit (Fig. 3a) is in the extreme north of the Pulau Seribu, totally isolated from any Java-derived freshwater contamination and beyond the limit of penetration of most weekend diving and tourist groups. The patch reef is relatively sheltered from weather by surrounding islands. In this northern extremity of the Pulau Seribu, the east-west elongation of islands and cays is less pronounced. Ringit cay itself is equant in plan. Pulau Ringit has a rampart which is emerged only at extreme low tide. The crestal zone to the north-east of the cay is considerably wider than on other flanks, in response to preferential coral growth in the most exposed location.

2.3.1 Sand Cay

(a) General Characteristics

Emergent sand cays occur on most reefs and are generally elliptical or arcuate in plan, ranging in length from 50 - 3000 m., and in width from 30 - 150 m. The initial locus of sand accumulation on the reef flat represents the focal point of waves refracting on the reef edge. Cays in the south of the Pulau Seribu group tend to be smaller relative to the reef area compared with those in the north (Plate 2b, 3a & b, 11f), although the southern cays are larger in absolute terms. Relief is very low attaining a maximum of approximately 2 m. above sealevel.

In the early stages of development, the cay is unstabilised and consists of a mobile sand wave which is reworked periodically by storm activity with resultant radical changes in shape. Such sand bodies are commonly flooded at high tide e.g. Pulau Kotok Kecil, Gosong Bira (Plate 2d). Such bodies build very rapidly once established although permanent survival depends on their attaining increased stability thorugh floral colonisation (Plate 6d). Between December 1983 and June 1984 the intertidal sandbank on the submerged northern reef of Pulau Kotok Kecil grew from a 10 m. long arcuate bank to a 25 m. long undulose ribbon-shaped body. Most cays are permanently emergent and stabilised by the growth of such vegetation as coconut trees and shrubs. The continued growth of the cays is evidenced by the development of intertidal spits at the eastern and western ends of cays, offshore bars and the encroachment of mangroves onto the reef flat (Plate 7c).

The Pulau Seribu exhibits five types of cay which, in order of increasing maturity are;

Type I submerged sand bar emergent only at low tide, e.g. reef immediately north of Pulau Kotok Kecil; Plate 2d,25d.

Type II low lying sand or shingle cay, e.g. Pulau Barang.

Type III lying cay with pioneer strandline plant community, e.g. Pulau Belanda.

Type IV higher standing cay with more complex better developed vegetation including trees, e.g. Pulau Putri Besar.

Type V sand cays with mangrove growth and sometimes mangrove swamps, e.g. Pulau Pari.

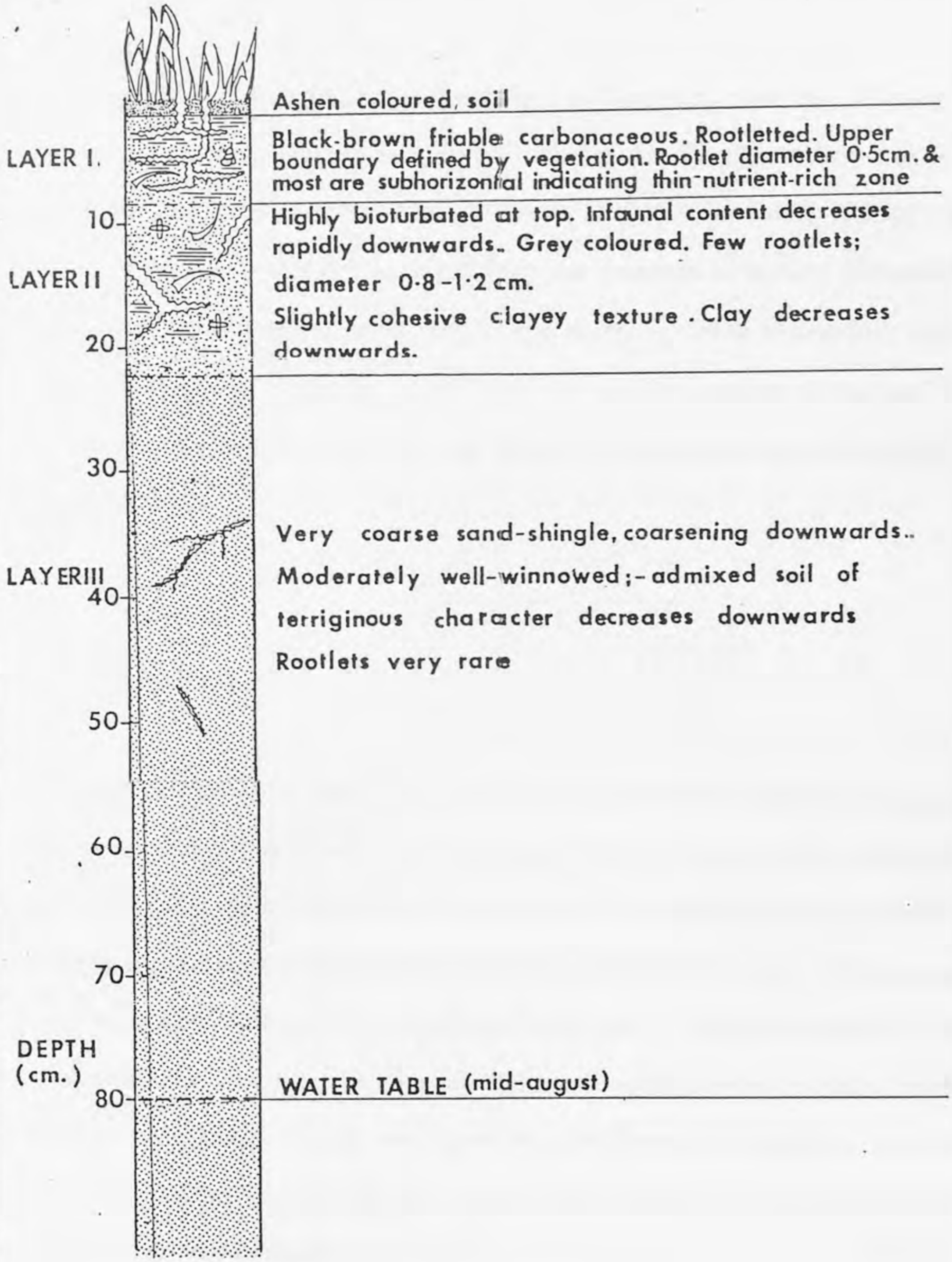


Figure 7 Typical cay-soil profile.

A number of soil pits approximately 1 m^2 in plan, were dug in the cay substrate and three soil layers were identified (Fig. 7). On the smaller cays (e.g. Pulau Kotok Kecil, Pulau Macan Kecil) the soil profile is immature and layers 2 and 3 are very thin. This is associated with the presence of a more pioneering-type of vegetation compared with that in the south. A fresh to brackish water lens is present on the vegetated islands and depth to the water table varies from 0.4 - 0.8 m. Sediments from the cay belong in the carbonaceous lithofacies (Section 2.6.3f).

(b) Intertidal Subzone

The margins of the cay are gently shelving intertidal beaches, mangrove clumps or mudflats (Plate 4-6). Intertidal sand flats can be very wide such as on Pulau Pari where 500 m. of sand is exposed intertidally during spring lows (Plate 5a). Bars of intertidally exposed sand prograde onto the reef flat. The beaches are sediment sinks and occur on the convex windward or exposed margins. They are ribbon-like in plan, 3 - 15 m. wide and trend approximately parallel to the reef edge. A pit dug through the intertidal sand revealed complete oxidation down to the water table. The well-sorted coarse sand is slightly aligned but exhibits no inclined bedding lamination or distinct burrows. This is attributed to pervasive bioturbation by crabs and shrimps.

In 1983, an attempt was made to drill through the intertidal zone using a hand-operated hydradrill. Although recovery was negligible due to the largely unconsolidated nature of the material, the exercise provided an idea of the depth of unconsolidated sand and the subsurface stratification. In the top 6 m., six indurated layers upto 8 cm. in thickness occurred, and between 6 - 11 m. depth numerous thin hard streaks were detected. These results are similar to the description of the first Funafuti reef boring in 1897 (Rodgers 1980) reported to have encountered cavernous core rock at 40-50' (13-16 m.) but otherwise just very loose organic sand.

Beaches slope gently seaward in a series of step-like wave-built berms or cuspate sand ramparts concave to the island. The texture is variable from coarse well-sorted sand in the lower intertidal zone to poorly-sorted shingle in the upper intertidal zone (Plate 4b). Coral fragments upto 50 cm. long are washed up on the beach. The fine burrowed intertidal sands are commonly pelleted on the southern shores of Pulau Pari (Plate 4c).

Beach sands belong in the winnowed coral-mollusc grainstone lithofacies (Section 2.6.3e). Sand-sized grains are moderately to highly rounded and abraded whilst the shingle fraction comprises subangular broken corals and broken or whole molluscs. Beaches are bound on the landward margin by a colonised bank which edges the elevated central portion of the cay (Plate 4a). A strandline of dead vegetation and scattered coarse skeletal fragments defines the uppermost intertidal limit. On sheltered margins this interfingers and grades in with the rooted vegetation, sometimes with a step of between 20 - 100 cm., for example on Pulau Pari.

The lower intertidal zone in sheltered areas is pock-marked with trails and tracks of the gastropod Ceritheum, and of the echinoid Marthasterias glacialis (Plate 4d). Commonly a very thin mucilaginous algal film of negligible cohesiveness forms a brownish scum on the sediment surface. A similar subtidal gelatinous film, though of rather greater cohesiveness, described by Bathurst (1967) was found to contain a large proportion of blue-green algae. On relatively exposed margins such as the eastern margin of Pulau Kotok Kecil and western margin of Pulau Ringit, the beach undercuts the vegetated cay and a soil profile is exposed in an 80 cm. undercut ledge. At such localities, the beach is generally slightly steeper and narrower and characterised by a molluscan assemblage resembling that of the agitated reef flat and notably devoid of the gastropod Ceritheum. A slightly more robust "tufted" filamentous algal layer is present rarely on such agitated intertidal shores. These films are only preserved for any length of time where they remain permanently beneath a thin film of water and therefore, where found, are a good indicator of marine phreatic conditions.

The lower limit of the beach is the low tide limit. The lower intertidal sands are commonly rippled in the ripple-swash zone (Plate 5c). Ripples are perpendicular to the wind direction and have a wavelength of approximately 0.5 metres and an amplitude of 1-2 cm. A pit dug in the lower intertidal sands at Pulau Pari revealed an anoxic layer (Plate 5b) from just below the surface to a depth of 8 cm. which is attributed to decay of organic matter. Below this layer the sands are again oxidised. The contact between oxidised and unoxidised layers is undulose and slightly burrowed. No bedding lamination is present. Conical burrows of the decapod Callianassa (Shinn 1968a; Plate 13b) are encountered within the intertidal zone of large reefs such as Pulau Pari and Pulau Ayer. Only there is there a sufficient depth of unconsolidated sand to accommodate these infauna. The tops of the Callianassa burrows are planed off by the falling tide (Plate 5d) but preserve an open exhalent hole. In troughs between the burrowed areas, tolerant species of Thallasia colonise. The troughs, which remain flooded except during exceptionally low tides, and the exposed sand spits, interdigitate. Sand spits prograde onto the reef flat in the lee of shingle bars or small new cays, thus the transition between intertidal and reef flat zones is gradational and consequently interlayering of the sediment is predicted in a vertical sequence.

Low energy margins of some cays, generally north-west facing concave rims, are characterised by development of intertidal mangrove mud flats (Plate 7c). These are found only on the large reefs where wide shallow bays such as that to the north-west of Pulau Pari, are isolated from the wind and wave energy on the outer reef edge. Mangrove roots help to baffle water movement and further dissipate hydrodynamic energy (Plate 6a). Sediments are fine dark oozy muds high in organic content (Plate 6c). The upper intertidal boundary here is also marked by a stable vegetated bank 0.5 - 1 m. high. The mud flats have very low relief, varying in width from 3 - 15 m., and the reefward boundary is gradational into the subtidal reef flat. The main member of the faunal and floral community is the mangrove Avicennia which grows either scattered or in dense thickets. Infaunal diversity is low and limited to scattered annelids, Callianassa and stonefish.

The mangrove muds are unbedded, lack lamination, and contain abundant mangrove rootlets. The surface of the mud is speckled with small gas holes 0.5 - 1 cm. in diameter (Plate 6b), and spaced approximately 6 cm. apart. The muds are commonly pelleted and patchily covered by a thin non-cohesive film of rustycoloured cyanophytic algae. Rare Callianassa burrows bring up medium to coarse grained sand to the surface. A trench dug in the muds reveals thoroughly homogenised sediment to 60cm. and below the surface the muds become anoxic and smell strongly of hydrogen sulphide.

Scattered mangroves do occur in exposed sites on reef flats for example at Pulau Petundang Kecil (Plate 7a), and so the presence of mangroves or mangrove rootlets in a cored section need not be indicative of a very sheltered environmental niche.

2.3.2 Reef Flat

The reef flat is a shallow carbonate platform which constitutes the greatest percentage of the total reef area. It is generally elliptical in shape, 15 - 30 m. wide and bordered seawards by the reef slope. The cay, where present, is asymmetrically located on the reef flat, generally on the western half (Plate 7b).

The reef flat slopes gently seaward from the intertidal subzone to a marginal 'moat' (Brown et al. 1982) 1 m. deep just inside the reef edge. Waves impinging on the reef edge encounter considerable frictional resistance due to the shallowness, and water energy is rapidly dissipated. Roberts (1980) using wave height changes, calculated that energy loss at the reef crest ranges from 70 - 90 %. Coral and algal growth on the reef flat occurs in a well-defined radial pattern (Plate 7a) which may result from channelised centrifugal draining of stale waters from the reef flat at low tide.

Sedimentary structures are varied and mainly of small scale. Lamination is absent but rippling is common on the windward shallow inner part of the reef flat especially on the extreme eastern and western edges of islands.

Symmetrical ripples with long axes orientated at a shallow angle to the reef edge, form in mobile uncolonised sand substrates, particularly at high tide when wave energy is less diminished by shingle ramparts. The amplitude of the structures is 1-2 cm. and wavelength approximately 6 cm. Current ripples are absent since directional currents are negligible inside the reef edge.

The reef flat comprises a number of subenvironments;

algal flat

sand flat

outer colonised moat.

(a) Algal Flat

The algal flat occurs on parts of the reef flat which are permanently submerged at a depth of 0.3 - 0.8 m. The community is composed of a mixed algal assemblage, the most common members of which are Thallassia, Padina, Sargassum, Zostera, Caulerpa and Halimeda. Areas of colonisation are elliptical or irregular in plan. Thallassia is a particularly prolific coloniser of low energy inner reef flats (e.g. north-west Pulau Pari). There the substrate is isolated from current and wave activity and the reef flat is protected in the lee of the curved cay margin. Thallassia is rooted into the sand in contrast to the majority of the other algae which anchor onto broken fragments of branched coral rubble which are scattered over the sediment surface.

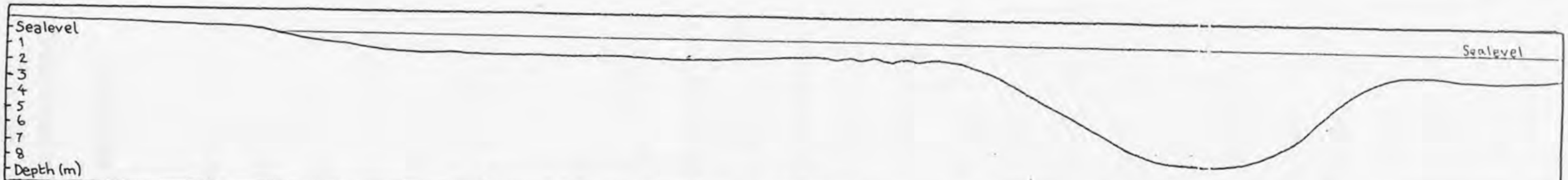
On the open agitated reef flat, the algal assemblage is more diverse and the associated fauna includes molluscs, sponges, holothurians, echinoderms and a wide range of organisms encrusting dead coral (Fig. 8, Plate 8a, 9a). Halimeda and Caulerpa are relatively uncommon except on the outermost algal patches near to the reef edge.

The algae baffle water movement thereby permitting the vertical accretion of hummocky, moderately to poorly sorted, slightly muddy, medium to coarse sand. The sediment is highly bioturbated and contains scattered disarticulated bored bivalves and fragmented encrusted corals. This belongs within the coral-mollusc-skeletal subfacies of the coral-mollusc packstone-rudstone lithofacies (Section 2.6.3a).

(b) Sand Flat

Sand flats are areas of mobile, largely barren and uncolonised shifting sand (Fig. 8, Plate 8b-d), which variously grade into algal flat, the outer colonised moat or intertidal bars. The depth of unconsolidated sand ranges from 5 cm. to greater than 1 metre. These uncolonised patches are composed of coarse sand, rare red algal nodules 20 - 80 cm. in diameter and scattered coral cobbles. The rubble varies from coarse shingle to boulders greater than 30 cm. in maximum dimension. Small patch reefs grow on the sand flat, increasing in size and frequency towards its reefward edge. Patch reefs are from 10 cm. - 1 m. in diameter and are composed of a low diversity coral assemblage (Plate 8d). Montipora ramosa comprises 80% of reef flat corals on Pulau Pari (Brown et al. 1982). The corals are bored by the tube worm Sabellastarte indica and encrusted by epilithic organisms.

On barren sandy patches, the echinoderm Diadema setosetum commonly clusters in hundreds, forming mobile thickets (Plate 10f) upto 8 m. across, whilst elsewhere holothurians (Plate 8c) rival Diadema in abundance. Near to breaks in the reef edge the sand flat sediment is winnowed and forms a carpet of coarse coral-mollusc grainstone.



	CAY	INTERTIDAL	SAND FLAT	ALGAL FLAT	LAGOON	MOAT
SEDIMENT CHARACTER	Thin soil layer present on mature cays (see Fig. 7)	Oscillating mobile sand shoal fringing cay and extending reefward in lobes and bars. Reefward inclined grain orientation. Very well-sorted. Rare encrusted abraded coral blocks. Upper intertidal margin disturbed by rootletting. Possible traces of carbonaceous material. Layers of very coarse sand and gravel from berms.	Slightly gravelly sand. Sediment virtually immobile, moderate-well sorted. Encrusted coral blocks. Unconsolidated sediment carpet variable from 8->40 cm. thickness.	Sediment mounded by Callianassa. Moderate-good sorting.	Sand-sandy silty mud. Bioturbated. Incursions of coarse-grained bored debris from lagoon edge patch reefs. Sediment pelleted. Murky low visibility.	Most sheltered from open sea and wave energy where a reef edge rampart is developed. Colonisation variable increasing reefward. Sediment carpet rippled and coarse grained. Moderate-well sorted.
BIOTA	Terriginous vegetation present where fresh or brackish water lens is present Rootlets penetrate shallow upper-most soil layer and are mainly subhorizontal.	Cerithiids, burrowing infaunal molluscs. Hydrogratus in subtidal depressions in between uncolonised intertidal bars.	Epibiont fauna, seagrasses especially Thallassia. Rare rhodophyta and codiacean algae. Clypeaster, Diadema setosum. Holothurians include Stichopus variegatus, Holothuria atra and Carapus. Lithothamnion, Euphyllia, Marthasterias glacialis, Haliclona communis, Aplysina aerophoba.	Rare boulder-type corals mainly faviid corals and Montastrea sp. Byssate and burrowing bivalves. Thallassia, Padina, Turbinaria conoides, Caulerpa, Clathrina, Phakelia, rare Halimeda and Lithotham. Holothuria, echinoderms, Dysatis kuhli, Diadema.	Thin shelled molluscs, Callianassa, Thallassia, Sargassum. Lagoon edge corals include Galaxea fasicularis, Porites sp., Pocillopora sp. and meandroid corals. Intermittent organic film. Holothurians.	Pocilloporidae includinge Paulastrea ramosa and Stylophora pistillata. Poritidae including Porites lutea, Porites andrewsi Favia flexuosa and Montastrea sp. Small Heliopora colonies. Lithothamnion nodules. Molluscs, Sabellastarte indica

Figure 8 Characteristic biota and sediments of the reef flat.

Parts of the sand flat on Pulau Pari and Pulau Pentundang Kecil are completely covered in conical *Callianassa* mounds (Plate 9e) which average 35 cm. in diameter and 20 cm. in height (Plate 10e). Adjacent burrows grade into and interfere with one another and in such areas there are few rooted colonisers since the slopes of the mounds continuously suffer small slips and the substrate is highly unstable. Sediment ejected from the exhalent hole drifts in the water column before being redeposited. Roberts *et al.* (1981) suggested that this is a significant agent of sediment transport and calculated that on intensely burrowed reef flats upto 3.9 kg.m^{-2}.day^{-1} of sediment may be ejected 5-10 cm. into the water column. Sediment is bioturbated to a depth of 20-50 cm. by *Callianassa* (Tudhope & Scoffin 1982) and selective biogenic size-sorting results in textural inhomogeneity. Grains finer than 250 - 500 µm. are preferentially worked into the upper levels of the bioturbated layer whilst coarse grains, predominantly fragmented mollusc shells, collect as a subsurface lag or are incorporated into the stiff mud lining which reinforces the walls of the exhalent vent. Biogenically constructed rosettes of gummed sand are also found around the exhalent hole of *Callianassa* mounds (Plate 10d). The rosettes are multi-layered, approximately 10 - 12 cm. in diameter and disintegrate on drying out.

Burrows represent special microenvironments (Fig. 9). The organic mucus-mud lining and the fill are of different texture and porosity, and probably different pH and Eh to the surrounding sediment. The production of faecal pellets within the burrow results in aggregation of calcilutite representing an alteration in the hydrodynamic properties of the sediment and hence a new diagenetic microenvironment.

On parts of some reef flats the sand forms a thin cover over a substrate of dead coral such as occurs on much of the northern sand flat of Pulau Pari