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GRAIN SIZE, CALCIUM CARBONATE CONTENT AND ACCUMULATION RATES OF RECENT SEDIMENTS IN PHANGNGA BAY, SOUTH THAILAND

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ABSTRACT

168 surface sediment samples and 46 short cores were collected from Phangnga Bay, South Thailand in January 1989 and January 1990. These samples have been analysed for grain size distributions and $CaCO_3$ content. The dėpositional enviroments have been distinguished on the basis of sea bed water depth, morphology and sediment grain size. The depositional environments are: mangrove channel; mangrove swamp; open intertidal; shallow marine; open marine; beach; reef and reef front. Mean grain size and sediment sorting show an overall increasing trend southwards (towards the more marine environment). $CaCO_3$ in the form of shell fragments also increases southwards as the diluting effect of terrigenous sediment decreases away from the dominant source of this sediment in the north. $CaCO_3$ also controls grain size distributions to some extent in that carbonate skeletal debris is the main component of the gravel size fraction and so high $CaCO_3$ values correspond to high gravel fraction values. Quartz sand abundance also increases towards the more open marine continental shelf environment and these samples are thought to represent relict sediments which were originally deposited in shallow marine or coastal plain environments when sea level was lower during the last glacial period. Seven wood and shell fragments from core sub-samples have been radiocarbon dated and accumulation and progradation rates calculated from these dates. Vertical apparent accumulation rates for the northern part of the bay for the last 6000 years vary between 0.3 and 1.53 mm year^{-1} and mangrove swamp lateral progradation rates have been estimated at 1.5-1.67 m year^{-1}.

INTRODUCTION

Objectives and Scope of Study

This study describes patterns of sedimentation in Phangnga Bay which is a tropical restricted bay encompassing a spectrum of sedimentary environments from mangrove swamps at the head of the bay in the north, through to fully marine open shelf conditions in the south. The objectives of the work reported here were as follows:

1. To describe the nature, grain size and calcium carbonate content of surface sediments across the area.

2. To determine average Late Holocene sediment accumulation rates, and mangrove progradation rates in the northern part of the bay.

Study Area

Phangnga Bay is situated on the west coast of Peninsular South Thailand (Fig.1) 8°C and 98°30E' in the tropical monsoonal area of South East Asia. The dry north easterly monsoon occurs from November to March whilst the wet south westerly monsoon extends from April to October. Rainfall is highly seasonal with an average of 300 mm/month in the wet season. Coastal waters vary in temperature between 26°C and 31°C. The bay encompasses approximately 1500 km^2 and is surrounded by a relatively small catchment area of approximately 2500 km^2. The bay is elongate north-south, the southern side being open to the Andaman Sea

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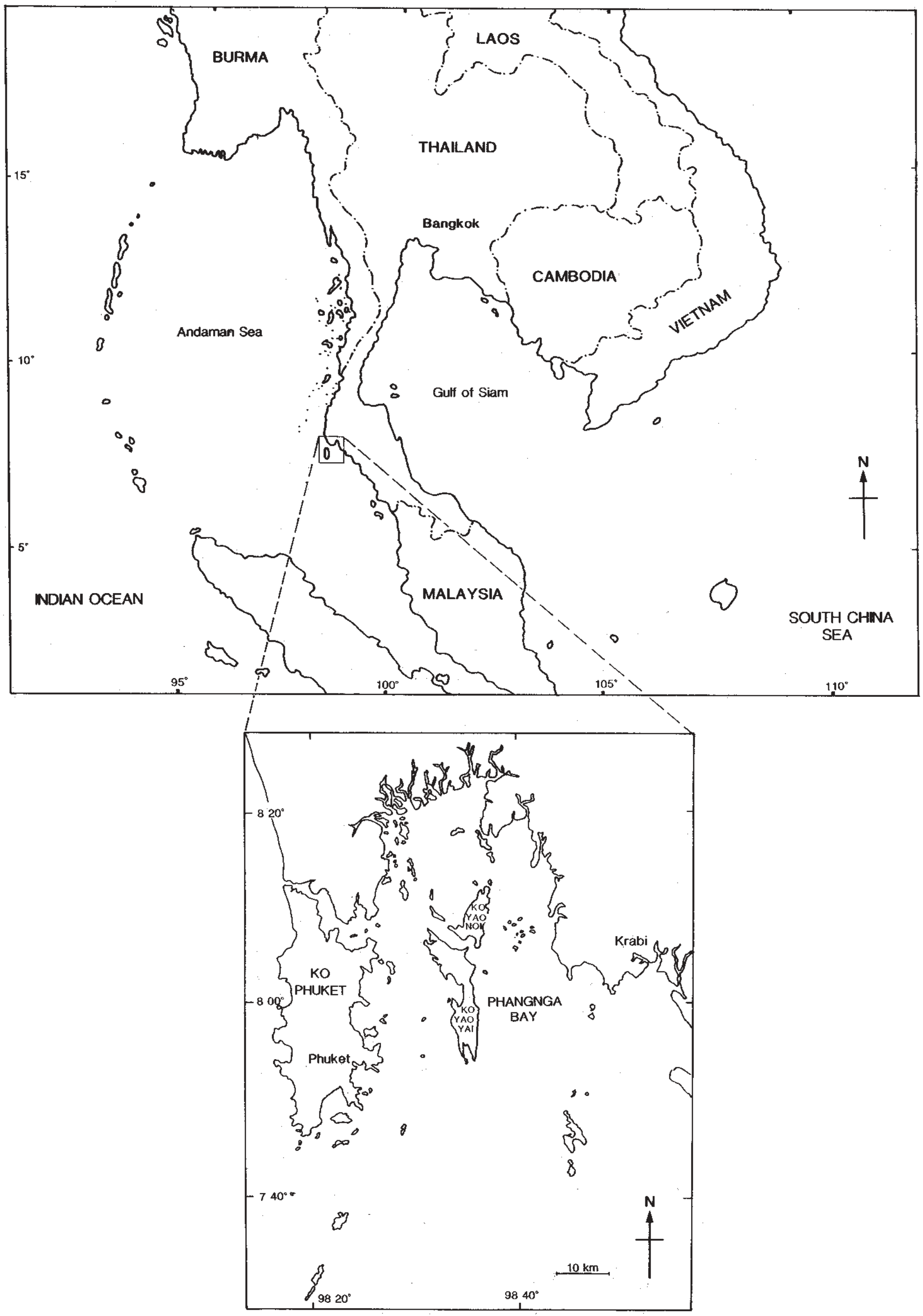


Figure 1. Location map of study area

whereas estuarine conditions prevail in the north. Much of the area north of Ko Yao Noi (Fig.1) is less than 5 m water depth, and depth increases to 65 m in the southern limit of the study area.

The estuarine environment is restricted to the northern limit of the Bay around the mangroves but its extent varies seasonally. In the rainy season the diluting effect of fresh water flow can extend up to 10 km further south into the Bay than in the dry season when lowered salinities (25-30 ppt) are restricted to mangrove areas (Limpsaichol, 1988). However, within this broad description there are a number of depositional environments which can be distinguished by the geomorphology and water depth of the deposits which result from them. Eight such environments have been distinguished; their distributions are illustrated in Fig.2

1. The **mangrove swamp** environment develops in the upper part of the intertidal zone and extends into the supratidal area (the latter area is not examined in this study). The largest development of mangrove swamps is around the northern coast of Phangnga Bay. There are smaller pockets in sheltered bays further south but these have not been sampled. The mangroves form very dense vegetation growing on soft grey-brown oxidised mud which becomes anoxic below 1-2cm (Limpsaichol, 1978).

2. The **mangrove channels** (up to 150 m wide at their mouths) are also located within the intertidal zone, dissecting the mangrove swamps and extending into the open intertidal zone. Some channels extend landward into entirely freshwater alluvial channels although most start as smaller channels within the mangroves.

3. The **open intertidal** environment extends from the mangrove swamp front to the lowest low water level although this boundary is gradational into the shallow marine environment (see below). The larger mangrove channels extend through the open intertidal zone and grade into the shallow marine environment with no exposure at low tide.

4. The **shallow marine** environment extends from the open intertidal environment and mangrove channel environment southwards and is entirely sub-tidal. The southern-most limit bounds with the open marine environment at the 20 m isobath.

5. The **open marine** environment extends seaward from the shallow marine enviroment at depths greater than 20 m, continuing outside of the field study area across the continental shelf.

6. The **beach** environment contains sand and gravel sediment deposited in the more exposed littoral areas which exist predominantly in bays in the southern part of the study area.

7. The **reef top** environment which consists of fringing reefs frequently with intertidal reef flats 100-200 m wide. The dominant frame-building coral is *Porites* but faviids and acroporids are also common (Brown and Holley, 1984).

8. The **reef front** environment in this area is generally a narrow (10-30 m wide) zone from 1-10 m water depth seaward of the reef where a mixture of reef-derived calcareous debris and a variable amount of terrigenous sediment accumulate on a gentle slope (Scoffin *et al.*, 1991)

Previous Work in Area

Previous investigations of Phangnga Bay have focused on aspects of water circulation (Siripong *et al.*, 1987) on resources and resource utilization (Limpsaichol, 1988) and on faunal distributions on mangrove shores (Frith *et al.*, 1976), reef flats (Nielsen, 1976, Brown and Holley, 1984 and Ditlev, 1978) and selected areas of the Peninsula west coast including southern regions of Phangnga Bay (Chatananthawej and Bussarawit, 1987 and Tantanasiriwong, 1978). On sediments, Limpsaichol

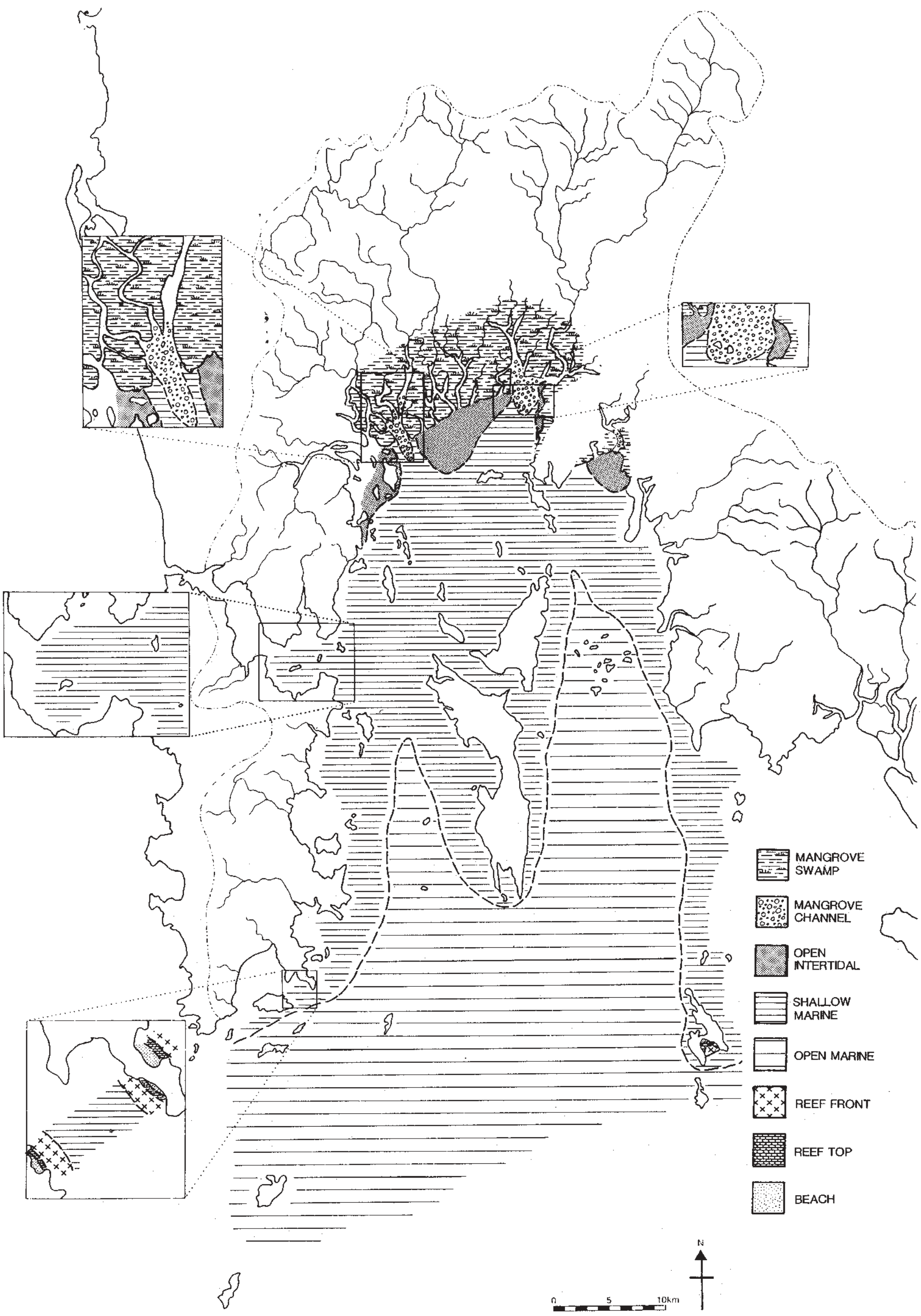


Figure 2. Distribution of depositional environments distinguished on the basis of elevation and sea bed morphology

(1978) investigated the redox potential of mangrove muds from the east coast of Phuket Island (south west Phangnga Bay) and Hylleberg *et al.*, (1985) described the effects of tin dredging on sediments on the west coast of Phuket Island. A detailed description of the geology of the catchment area of the bay is given by Garson *et al.* (1975).

METHODS

Collection and Storage

Surface sediment samples were collected from the Phuket Marine Biological Centre (PMBC) research vessel No 14 in 2 field seasons. Sites 1-63 (see Fig.3) were sampled between 17th and 20th January 1989 and sites 64-139 (including transects) were sampled between 5th and 9th January 1990. The distribution of sampling sites reflects an attempt to gain a good areal coverage of the area as well as to assess the degree of local variation at a few selected sites. In the north, 2 transects cross mangrove channel mouths and one runs from the mangrove front over the intertidal flat. In the south, one transect crosses the beach and reef at Tang Khen and another runs from the Aquarium beach across to Ko Lon (these samples are labelled T.K.1-6 and Aq-K11-17 respectively) (see Fig.3). Surface sediment samples were collected by 2 methods depending on the water depth. For water depths greater than approximately 5 m a Van Veen type grab was used from the research vessel. For shallower sites SCUBA equipment was used from a small boat to collect the surface sediment with a hand held scoop. To enable accurate grain size determination it was essential to preserve the sediments wet to prevent any aggregation of clays through drying. Immediately after collection of the top 5 cm of the sediment it was scooped into a plastic bottle, sealed and stored on ice until returning to the laboratory where the sediments were treated with 30% hydrogen peroxide (H_2O_2) to remove organic matter thus preventing deterioration of the sample during transit back to Britain. A sub-sample of sediment for chemical analysis was also collected from the grab sample and stored in a sealed plastic bag before oven drying at 55°C.

Cores were taken from a selection of sites (marked "C" on Fig.3) using either a gravity corer operated from the research vessel (see Fig. 4a) or with a length of 4 cm diameter plastic piping manually pushed in and retrieved from the sediment in shallow areas. The success of the gravity corer used from the research vessel depended on the sediment type - if it was of sand or gravel grain size then there was virtually no core penetration; if the sediment was muddy then recovery was good (30-60 cm). The manual method of coring was very successful and cores of up to 2.5 m in length were retrieved. The cored sediments were extruded (see Fig.4b) and sliced at 1 cm intervals for the top 10 cm and at 2 cm intervals thereafter. Each subsample was stored in a sealed plastic bag on ice before weighing, drying and reweighing in the laboratory to obtain the water content of the sediment and thus calculate the amount of compaction downcore.

Dry bulk density measurements were made on the cored sediment in order to take account of compaction when calculating sediment accumulation rates. The dry bulk density calculaltion is as follows:

$$\text{Dry Bulk Density} = \frac{\text{Mass of Dry Sediment}}{(\text{Mass of Dry Sed.}/2.45) + (\text{Mass of Water}/1.02)}$$

The average density of the sediment is taken as 2.45 g cm^{-3} and the density of seawater is taken as 1.02 g cm^{-3}. A slight correction is made to account for the salt content of the sediment. The dry bulk density describes the density of the sediment in relation to the volume of the sediment and the water as a whole. As the sediment is compacted with depth, water is expelled and the dry bulk density increases. The dry bulk density varies, however, with the grain size composition of the sediment. Fine grained sediments have a greater volume of pore spaces, therefore higher water contents (hence lower dry bulk density) than coarse grained sediments.

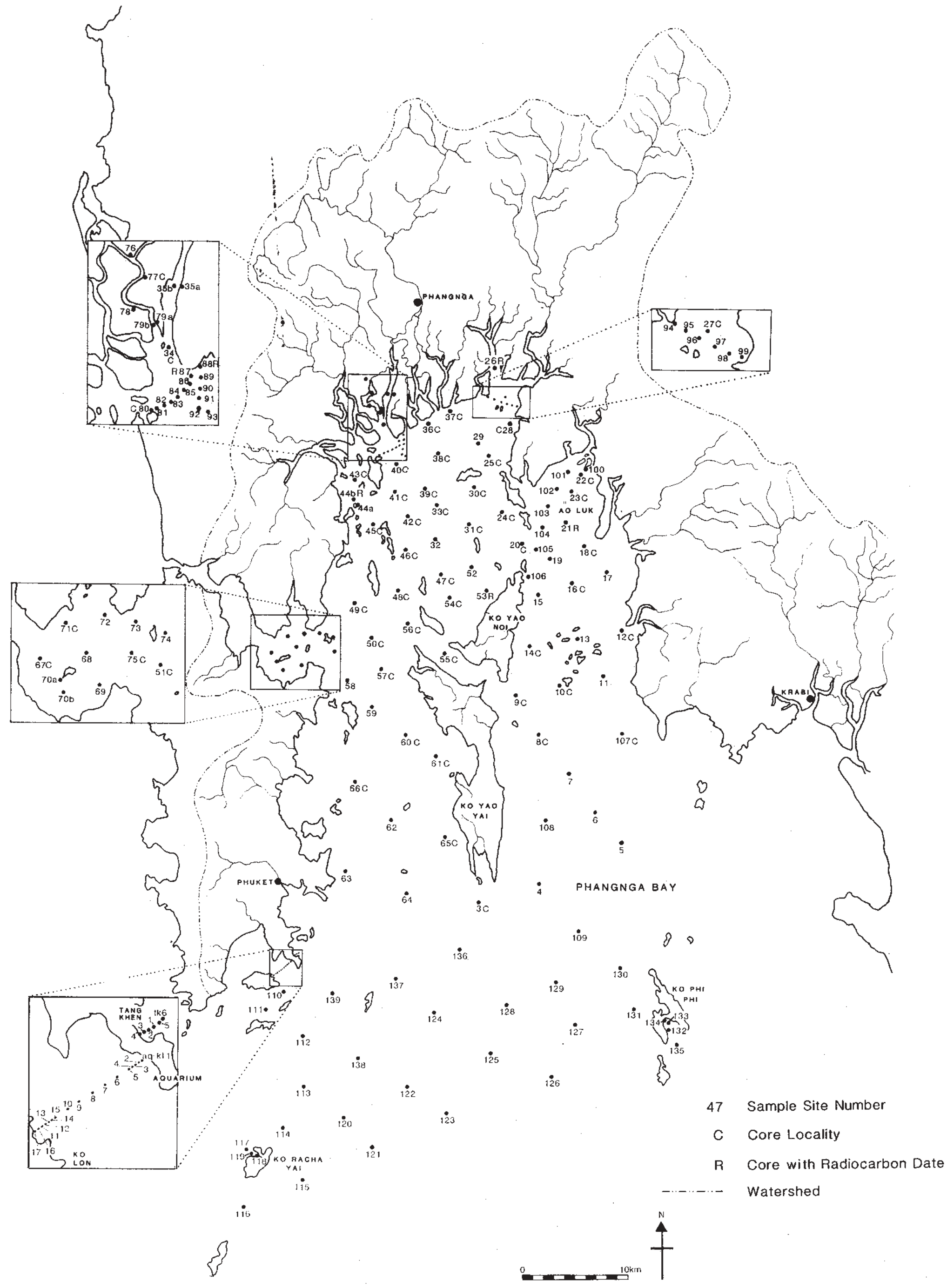
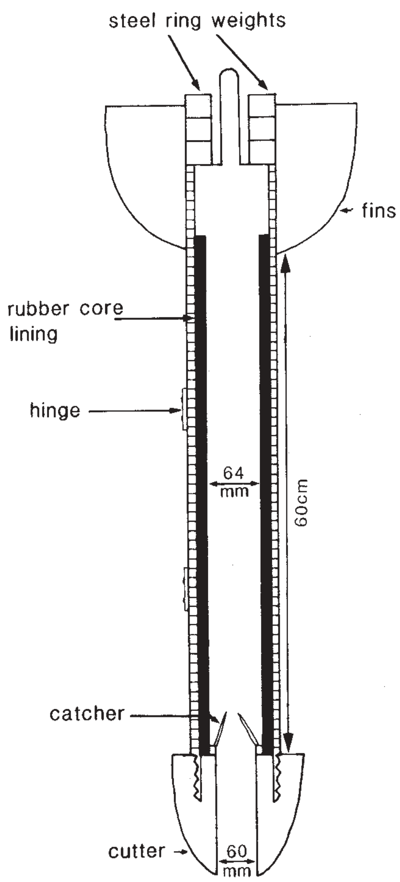


Figure 3. Distribution of sample sites throughout Phangnga Bay, Extent of watershed and main drainage system is also shown



Figures 4a. Gravity corer used from research vessel.

In order to compact the column of sediment down to the degree of compaction at the base of a sequence of sediments the following formula is used for each subsample:

$$\alpha = \frac{A \times \beta}{B}$$

where:

α = thickness of subsample after compaction correction
β = thickness of subsample prior to compaction correction
A = dry bulk density of subsample
B = dry bulk density of sample at base of sequence

$CaCO_3$ Content Determination

In order to calculate the $CaCO_3$ content of the sediments, the amount of Ca in each sample was measured using X-ray fluorescence

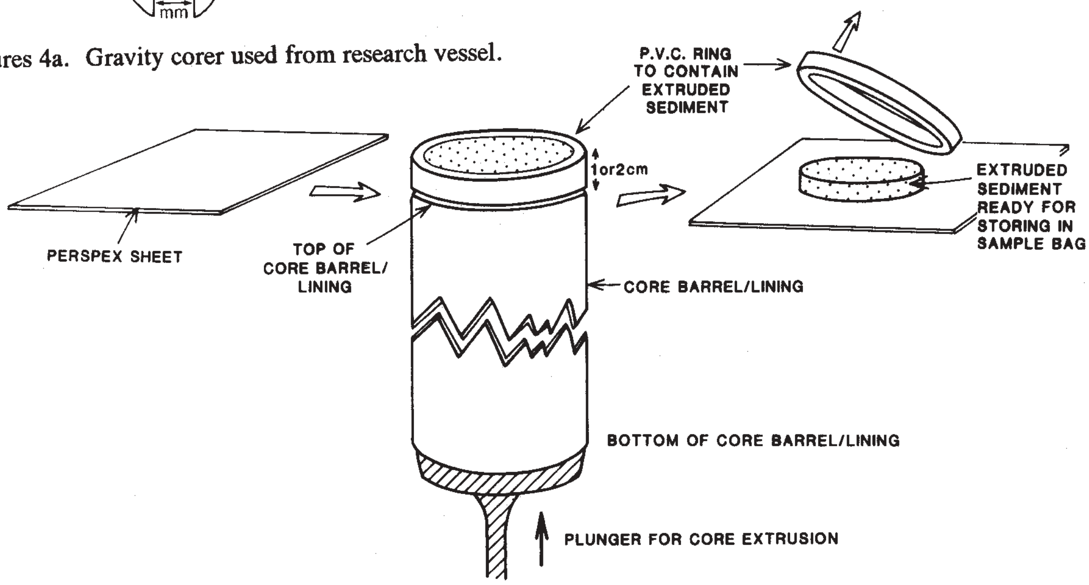


Figure 4b. Technique for extruding sediment from core.

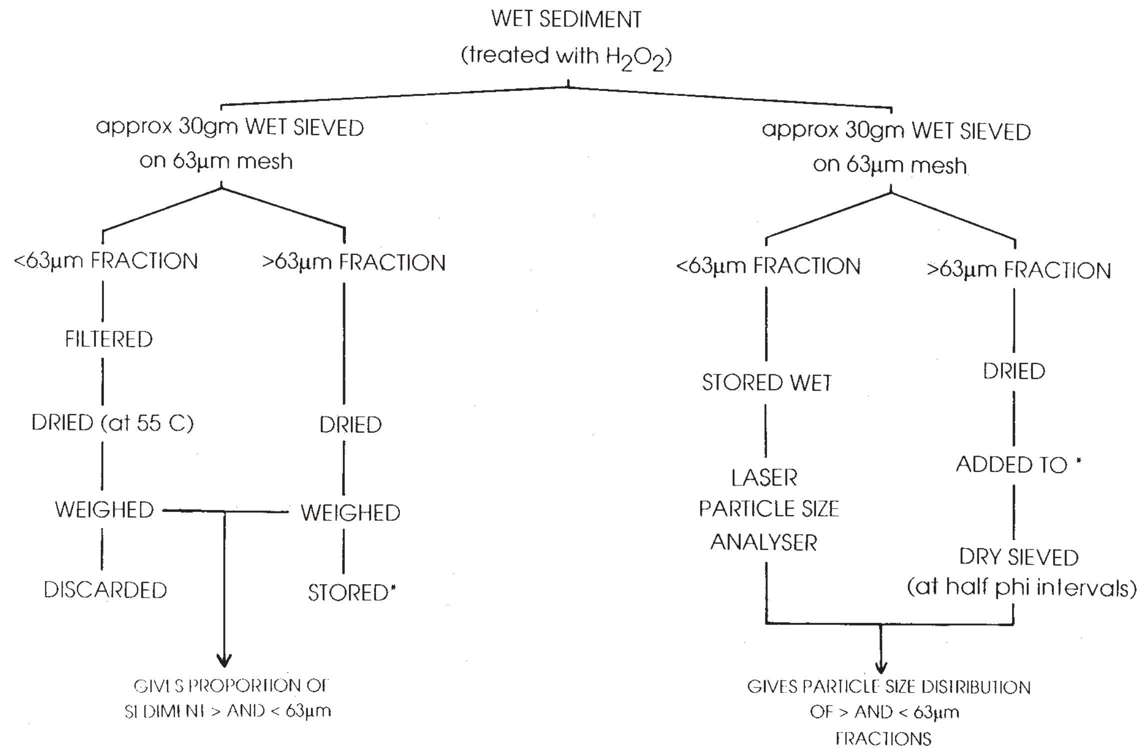


Figure 5. Flow diagram of grain size analysis technique

spectrometry. This method is considered accurate as X-ray diffraction analysis of the mineralogical content of the samples indicates that neither dolomite nor Ca-bearing clays are present in the samples and therefore all Ca measured is from $CaCO_3$. The samples were ground to less than 2 μm in an agate tema mill and then fused into glass discs following the method of Norrish and Hutton (1969) which were then run through a Philips PW1480 X-Ray Spectrometer. The analytical precision is 0.052% and the accuracy of the whole technique is 0.14% (these figures are calculated from 10 repeat analyses of one sample). Multiplying the Ca percentage by 2.5 gives the $CaCO_3$ content.

Grain Size Determination

To enable a detailed and complete measurement of the spread of grain sizes in each sample, 2 methods of analysis were used for different grain size fractions and the results combined. The >63 μm "coarse" fraction was dry sieved and the <63 μm "fine" fraction was analysed using a laser particle size analyser. A summary of the whole process is illustrated in Fig.5.

The >63 μm fraction was dry sieved using a nest of sieves at half phi mesh size intervals on a sieve shaker for 12 minutes. Each fraction was then weighed to the nearest 0.01 g. The fine fraction was analysed on a Coulter Laser LS-100 particle size analyser and the results collected in half phi intervals up to 12 phi and combined with the coarse fraction data from dry sieving.

Since this method of grain size determination provides the full size distribution of the sediment the moments method of analysing the grain size distribution was employed. This method uses the entire grain population which provides more representative parameters than the graphically derived values (McManus, 1988). The formulae for the first moment (mean) and second moment (standard deviation) are as follows:

$$\text{Mean (first moment):} \quad \chi = \frac{\Sigma f\, m\varphi}{100}$$

$$\text{Standard Deviation (second moment)} \quad \sigma^2 = \frac{\Sigma f\, (m\phi - \chi)^2}{100}$$

where f is the percentage fraction in each class interval of the total weight of sediment and m is the mid-point interval of each class interval in phi units.

Radiocarbon Dating

In order to calculate accumulation rates of sediment in the Bay, 7 samples of shell and wood from cores were radiocarbon dated by accelerater mass spectrometry at the AMS Unit, Oxford, Britian. Samples were taken from a range of depths in 6 different cores distributed around the northern part of the Bay (sites labelled "R" on Fig.3)

RESULTS

Distribution of $CaCO_3$ in Surface Sediments

The areal distribution of $CaCO_3$ in the surface sediments of Phangnga Bay is illustrated in Figure 6. Most of the $CaCO_3$ in the sediments is from the whole and fragmented skeletal remains of bivalves, gastropods, barnacles, foraminifera, pteropods, arthropods, echinoids, starfish, corals, bryozoans and calcareous red and green algae. Visual inspection of the sediments whilst sieving did not reveal any evidence of limestone fragments.

In general terms there is an increase in the $CaCO_3$ content of the sediments from north to south (Fig.6). Within this general trend there are variations in $CaCO_3$ content notably in the northern area where patches of high $CaCO_3$ (>30%) are surrounded by sediments with <10% $CaCO_3$. In the southern part of the bay $CaCO_3$ contents of >30% are concentrated in the western and southern area and around beach and reef environments.

Grain Size Characteristics of Surface Sediments

The areal distribution of mean grain size is illustrated in Figure 7. It is evident that there is a general trend of increasing grain size from the north to the south. The northern area of the bay is dominated by coarse quartz silts (4-6 phi) and areas of medium to fine quartz silts (>6 phi). The central and southern area is dominated by fine quartz sand (2-4 phi) and the extreme southern area around Ko Racha is dominated by medium to coarse quartz and carbonate sands and gravels (2 to -2 phi). In the northern half of the bay there are patches of coarser sediments within the dominantly silty and muddy area. Around the northern mangroves these coarser sediments are coincident with the mangrove channels and are composed of quartz and occasional feldspar grains. The small area of coarse sediments on the northern tip of Ko Yao Noi (sampled at site 106) and other patches of coarse sediments are coincident with areas of high $CaCO_3$ content (see Fig.6). In the southern area the coarsest sediments (0 to -2 phi) are coincident with areas of strong currents around Ko Racha. The samples from beaches and reefs on Ko Racha, Ko Phi Phi and South East Phuket show a coarser mean grain size than the surrounding shallow and open marine seiment. The clay fraction is composed of kaolinite, illite and montmorillonite (from detailed X-ray Diffraction analysis).

Fig.8 illustrates the areal distribution of sorting values for the surface sediments of Phangnga Bay. Like the mean grain size distribution, a general trend can be seen. This is an increase in sorting (decrease in standard deviation phi values) from north to south.

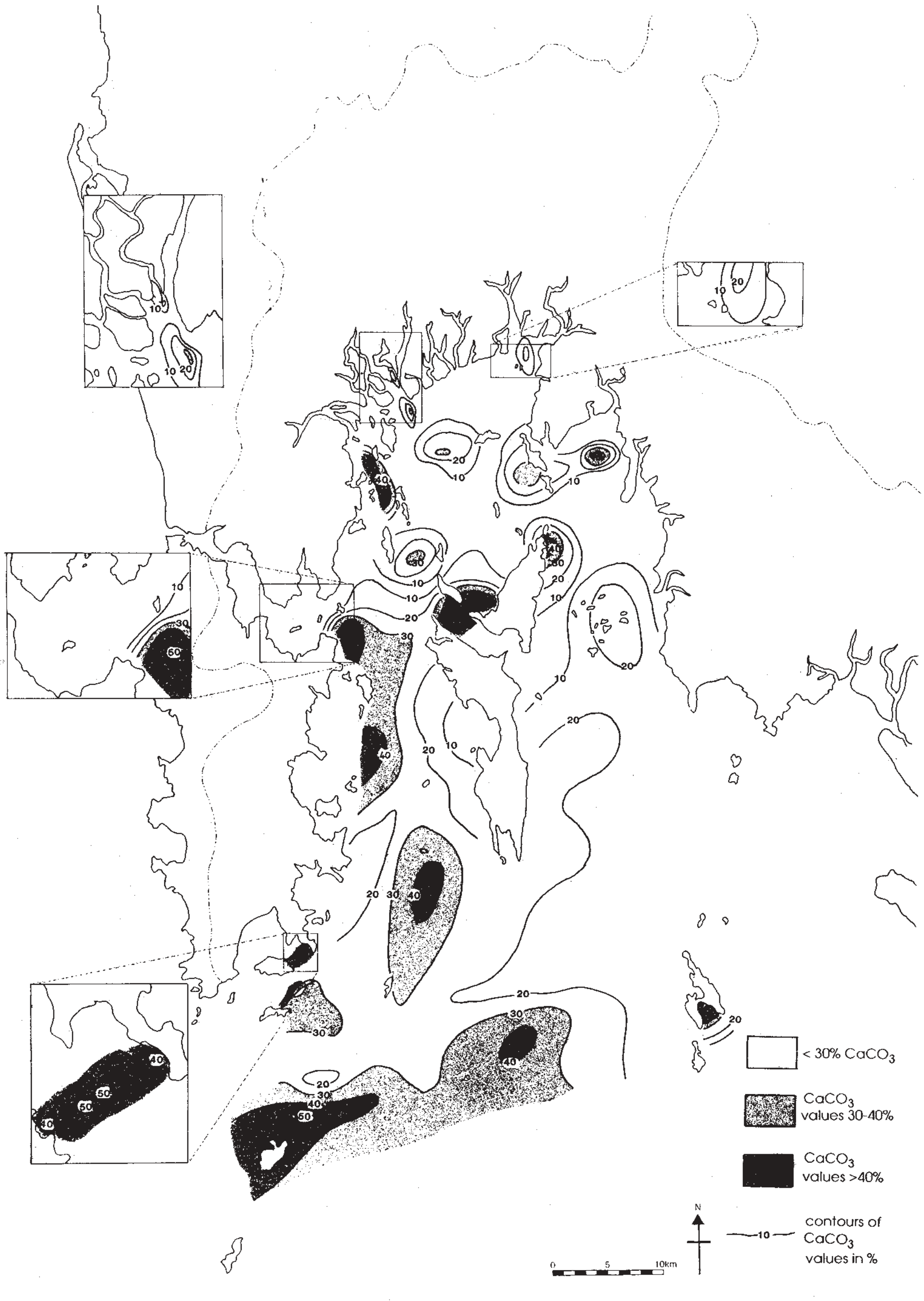


Figure 6. Distribution of calcium carbonate percent values

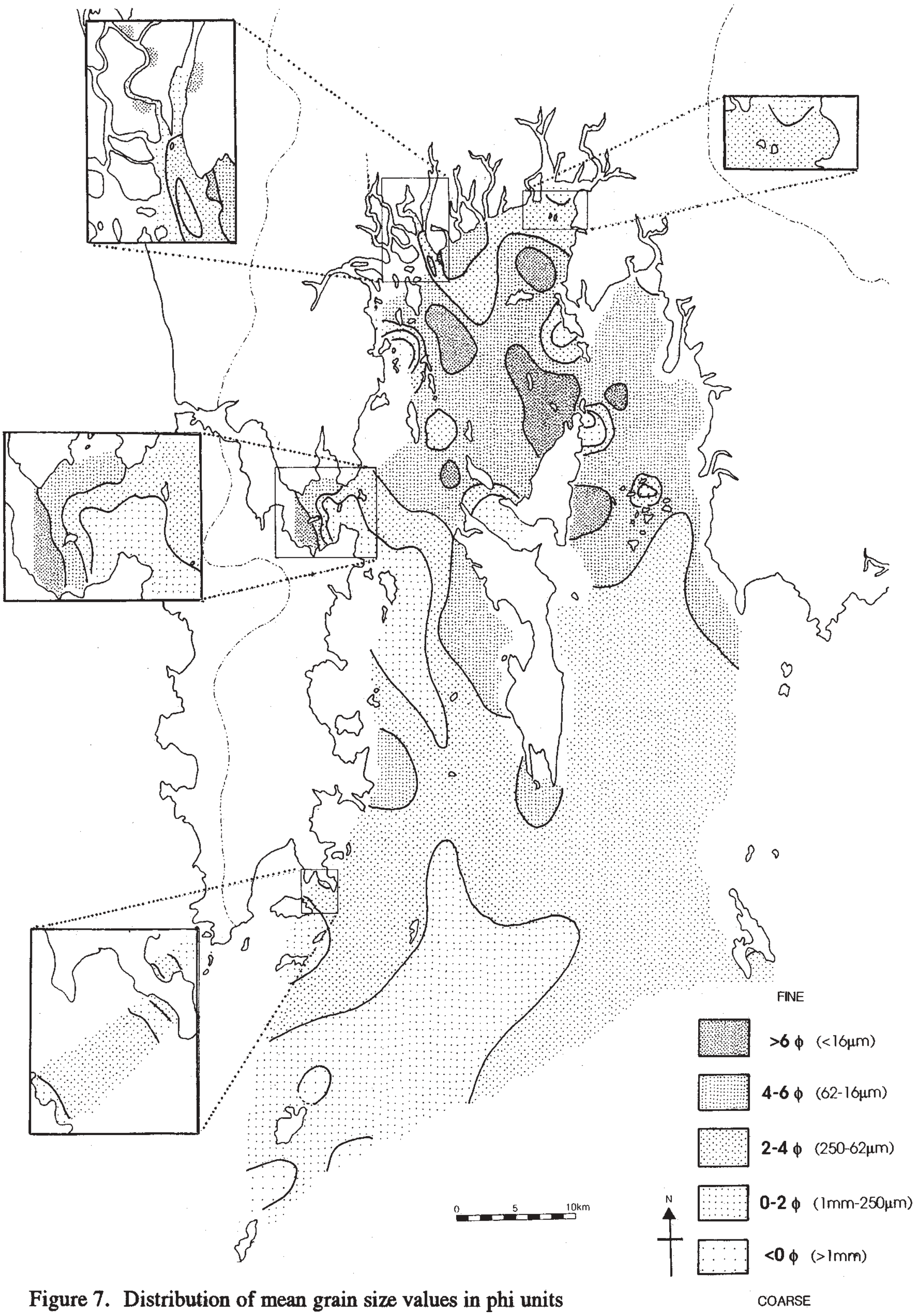


Figure 7. Distribution of mean grain size values in phi units

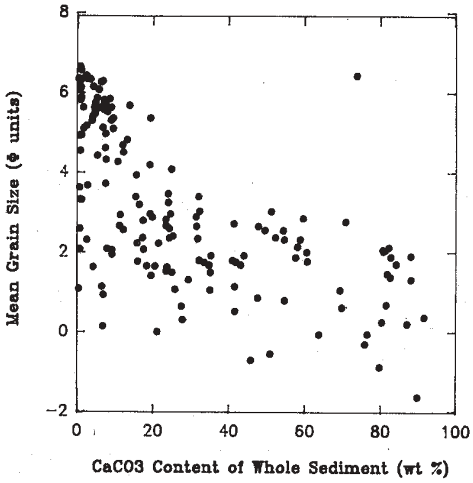
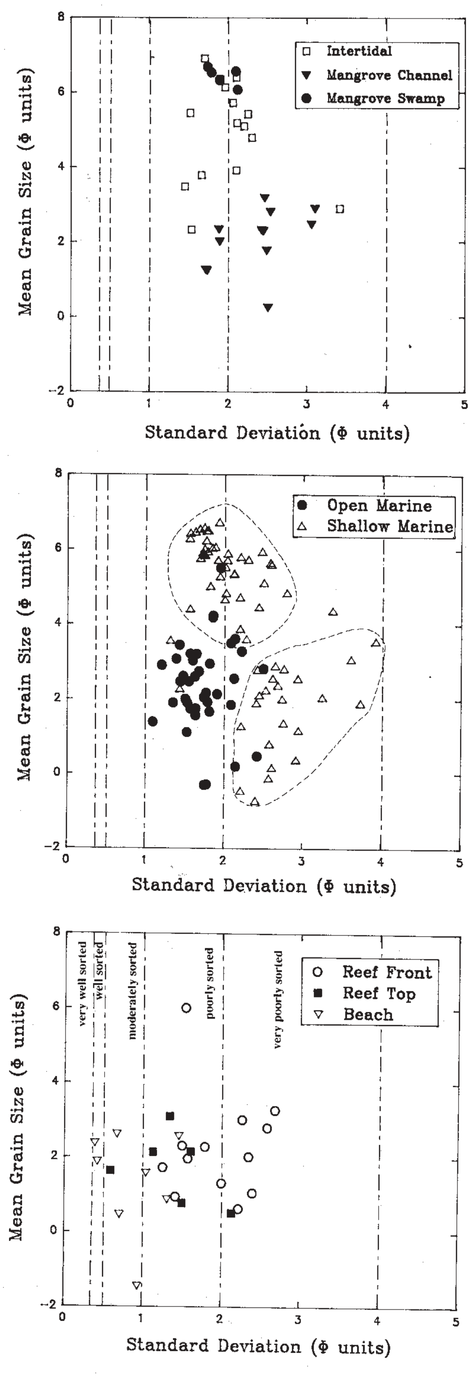


Figure 9. Graph of relationship between calcium carbonate content and mean grain size.

The pattern in the northern part of the Bay is, like mean grain size, more complicated than in the southern area. Patches of poorly sorted sediment (>2.5 phi standard deviation) coincide with the areas of coarse mean grain size and hence with areas of high $CaCO_3$ content. The exceptions to this are the mangrove channels where coarse mean grain size and poor sorting do not relate to high $CaCO_3$ content.

Fig.9 illustrates the relationship between $CaCO_3$ content and mean grain size of the sediment. In general there is a relationship of increasing $CaCO_3$ with increasing grain size (decreasing phi). This along with visual inspection of sediments shows that $CaCO_3$ occurs mainly as sand and gravel size fragments.

The relationship between mean grain size, standard deviation and depositional environments as determined by bathymetry and sea bed morphology is illustrated in Figure 10. Fig.10a illustrates the sediment differences between the intertidal, mangrove channel and mangrove swamp environments. Clearly mangrove swamps have a finer grain size and less variation between samples than the mangrove channel sediments.



Figures 10a-c. Graphs of mean grain size versus standard deviation for individual depositional environments.

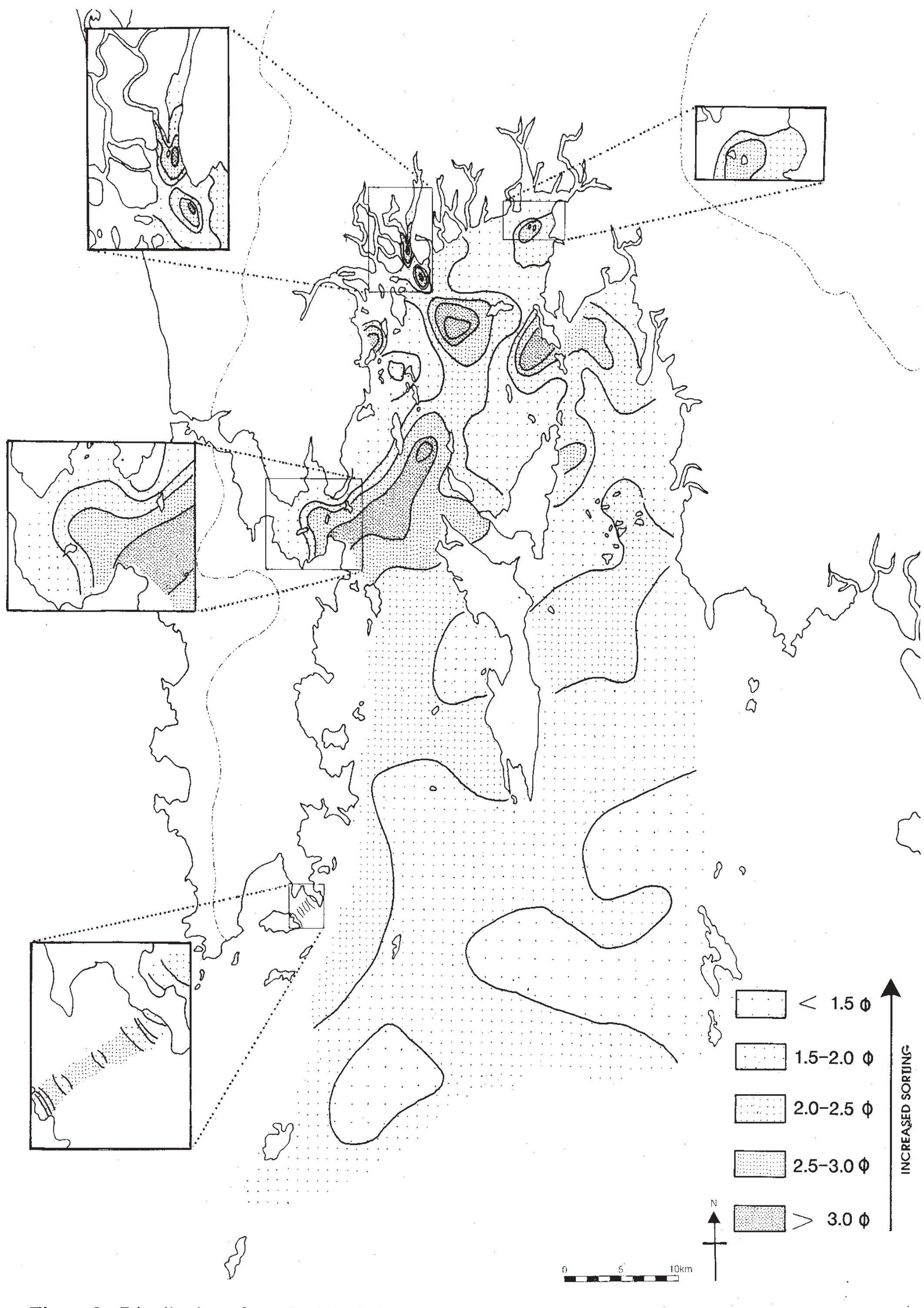


Figure 8. Distribution of standard deviation (sorting) values in phi unit

The intertidal sediments are more variable than both the mangrove environments and range from fine muds typical of the mangrove swamp sediments to poorly sorted sands typical of the mangrove channel environments. Fig.10b plots the sediment characteristics of the shallow and open marine environments. The open marine sediments are all clustered around the medium to fine sand mean and around the 1 to 2.5 phi standard deviation. Compared to the shallow marine sediments they tend to be coarser and better sorted. The shallow marine sediments show a much wider variation and may even be split into two groups (delineated by dotted lines on the graph) one of poorly sorted, coarse sediments and another of better sorted fine sediments similar to the mangrove swamp sediments. Finally, Fig.10c illustrates the sediment grain size characteristics of the beach, reef top and reef front environments. These sediments are mostly coarse grained but show varying degrees of sorting. The beach deposits are the best sorted of all the environments studied with standard deviations of 0-1.5 phi. The reef top sediments are better sorted than the reef front sediment.

Fig.11 plots typical grain size frequency distributions of the different depositional environments of Phangnga Bay. The mean and standard deviation for each example are also plotted and they summarise the characteristic sediment parameters for each environment described above.

Accumulation Rates and Progradation Rates

The radiocarbon dates obtained from AMS dating of 7 samples are listed in Table 1. Correction of -450±35 years for all shell sample dates has been applied to account for the apparent age of marine carbonate [from the age of Australian coastal water carbonate (Gillespie and Pollach, 1979) as there is no available age for Thai coastal waters] and +40 years to correct ages to the date of collection as all dates are determined as radiocarbon year B.P., *i.e* 1950.

Soft sediment cores consist of an upper part which has a high water content and therefore relatively low bulk density, above compacted and dewatered sediment of relatively high bulk density (Table 2). Consequently, sediment accumulation rates may be expressed in a variety of different ways:

1. An average accumulation rate (in mm year^{-1}) determined by dividing the thickness of the core by the time it took to accumulate (apparent accumulation rate, AAR).

2. An average accumulation rate of **compacted** sediment (in mm year^{-1}) determined by "compacting" the core to the dry bulk density of the lower part. This accumulation rate approximates that which would be determined for an equivalent sedimentary rock record (compacted accumulation rate, CAR).

3. An average accumulation rate of **uncompacted** sediment on the sea bed (in mm year^{-1}) determined by "decompacting" the core to the dry bulk density of the surface and then dividing the expanded thickness by the time taken for it to deposit. This approximates to the net sediment accumulation experienced by sessile benthos (uncompacted accumulation rate, UAR).

4. A net sediment accumulation rate expressed in g cm^{-2} year^{-1}, determined by dividing the mean dry bulk density of the cored sediment by the time it took to accumulate (flux).

These 4 values have been calculated for core 53 and are listed in Table 2. Because of the change in dry bulk density caused by a change in grain size down core these calculations cannot be made on all cores

Radiocarbon dates not only provide an indication of the vertical accumulation of sediment but also help in trying to measure the horizontal accumulation or progradation rate of the entire mangrove system. In the calculation

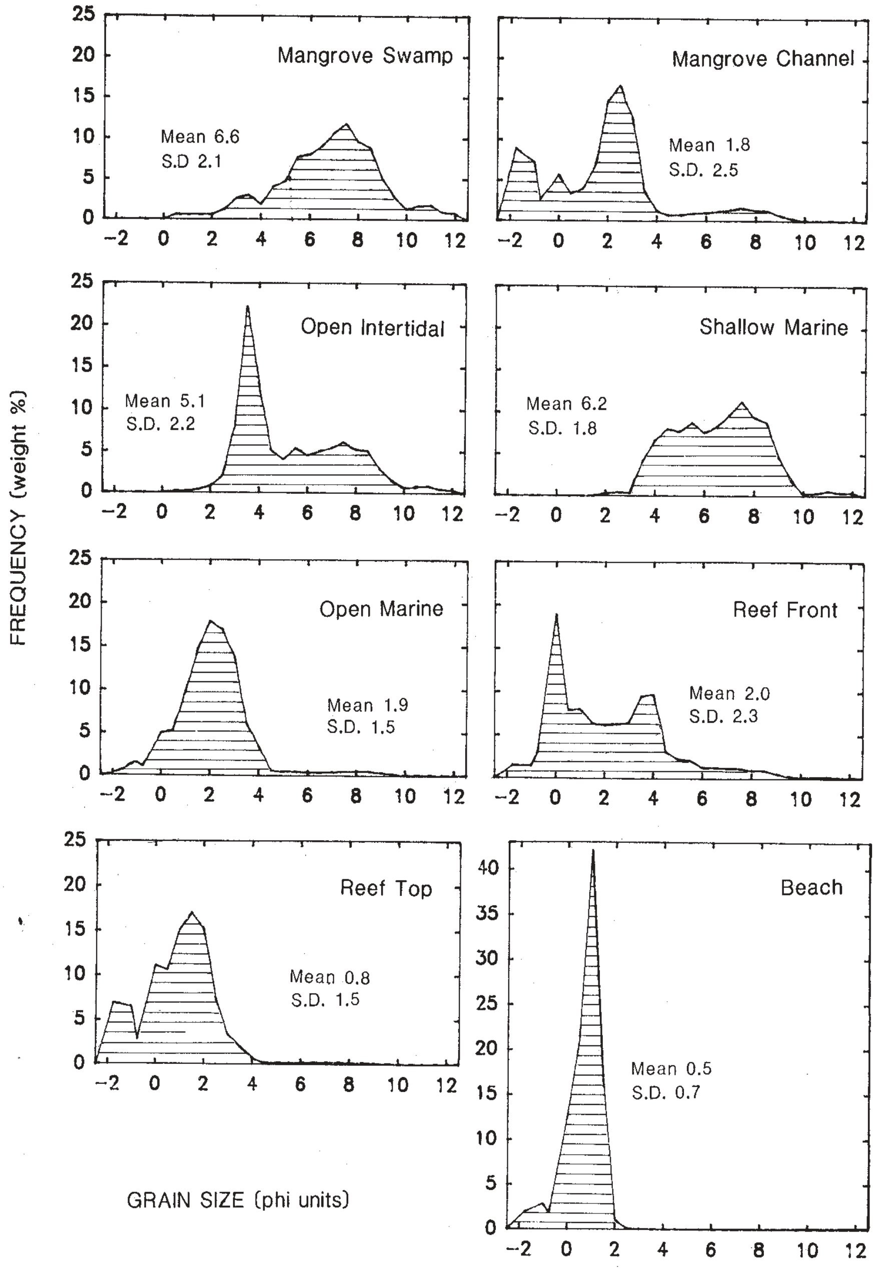


Figure 11. Grain size distribution frequency diagrams for the individual depositional environments (half phi intervals).

of the progradation rate, two methods have been used:

1. An estimate of average progradation rate of the mangrove system since 6000 years ago when the sea reached its present level following the Holocene transgression may be achieved by dividing the width of intertidal mangrove cover (10 km) by 6000. This yields

Table 1. Radiocarbon dates of samples from core sub-samples obtained from Oxford University Radiocarbon Accelerator Unit) and the calculated sediment accumulation rates.

Laboratory Reference	Core No.	Depth down core (cm)	Uncorrected Sample Type	Corrected ^{14}C Age (years)*	Age (years)#	Apparent Accumulation Rate (mm/year)
OxA-2699	21	30-32	*Paphia undulata* (infaunal bivalve)	1440 ±60	1030 ±69	0.3 ±0.02
OxA-2700	26	28-30	wood fragment (?mangrove)	150 ±60	190 ±60	1.53 ±0.5
OxA-2701	44	44-46	*Ostrea sp.* (oyster)	3220 ±70	2810 ±78	0.15 ±0.006
OxA-2702	44	26-28	*Paphia gallus* (infaunal bivalve)	820 ±60	410 ±69	0.66 ±0.1
OxA-2703	53	46-48	*Paphia undulata* (infaunal bivalve)	720 ±60	310 ±69	1.52 ±0.3
OxA-2704	87	185-190	Barnacle fragment	1980 ±70	1570 ±78	1.19 ±0.06
OxA-2705	88	210-215	*Ostrea sp.* (oyster)	2170 ±70	1760 ±78	1.2 ±0.06

* the age in radiocarbon years B.P. (Before Present - AD 1950) provided by the Oxford AMS laboratory.

the age in radiocarbon years before year of collection (1990) and with a marine reservoir correction.

an average progradation rate of 1.67 m year^{-1} (Fig.12a). This value is a minimum, which ignores the possibility that landward alluvial deposits may have reduced the width of the mangrove swamp.

2. A second estimate of progradation rate may be made by consideration of bathymetry of the sea bed in front of the present mangroves, and applying our calculated average vertical sediment accumulation rates in this environment (Fig.12b). This method yields a projected mangrove progradation rate of about 1.5 m year^{-1}.

DISCUSSION

The north end of Phangnga Bay is dominated by muds. This is a result of a combination of factors, including the following:

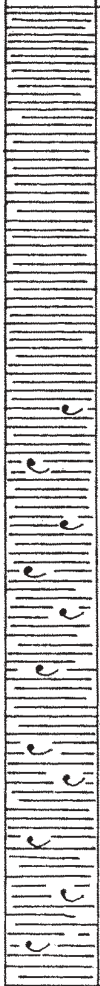
1. proximity to source of the weathered products of granites (predominantly kaolinite).

2. low wave energy consequent on the shelter afforded by the enveloping landmasses.

3. low tidal energy due to the restricted, semi-enclosed setting.

4. Flocculation of colloids occurs as fresh and salt water meet, resulting in the settling out of fine grained, clay sediment.

Table 2. Dry bulk density, pre-and post-compaction calculations for Core 53. A.A.R.:apparent accumulation rate; C.A.R.:compacted accumulation rate; U.A.R.:uncompacted sedimentation rate.

Log	Depth (cm)	Present Thickness of core	Dry Bulk Density (gm/cm³)	Thickness after Compaction	Thickness before Compaction
	0-1	1cm	0.248	0.35cm	1.00cm
	1-2	1	0.319	0.45	1.29
	2-3	1	0.340	0.48	1.35
	3-4	1	0.403	0.56	1.62
	4-5	1	0.405	0.57	1.63
	5-6	1	0.424	0.59	1.71
	6-7	1	0.436	0.61	1.76
	7-8	1	0.466	0.65	1.88
	8-9	1	0.499	0.70	2.01
	9-10	1	0.497	0.70	2.00
	10-12	2cm	0.531	1.49cm	4.28cm
	12-14	2	0.534	1.50	4.31
	14-16	2	0.530	1.48	4.27
	16-18	2	0.525	1.47	4.23
	18-20	2	0.503	1.41	4.06
	20-22	2	0.577	1.62	4.65
	22-24	2	0.534	1.49	4.31
	24-26	2	0.557	1.56	4.49
	26-28	2	0.567	1.60	4.57
	28-30	2	0.608	1.70	4.90
	30-32	2	0.592	1.66	4.77
	32-34	2	0.561	1.57	4.52
	34-36	2	0.579	1.62	4.67
	36-38	2	0.625	1.75	5.04
	38-40	2	0.624	1.75	5.03
	40-42	2	0.617	1.73	4.98
	42-44	2	0.584	1.64	4.71
	44-46	2	0.598	1.67	4.82
	46-48	2	0.714	2.00	3.76
Total Thickness (cm)		48		36.4	103.6
A.A.R. (mm/year) C.A.R. (mm/year) U.A.R. (mm/year)		1.52		1.17	3.3
Mean dry bulk density (gm/cm²) Flux = 1.67 mg/cm²/year			0.517		

CORE 53