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Patterns of coral reef degradation along the west coast of Sumatra, Indonesia

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Zentrum für Marine Tropenökologie
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Abstract

Multivariate non-parametric characterisation of coral reef communities was used to compare reef sites under different environmental impact regimes in West Sumatra, Indonesia. The study was based on the assessment of (a) differences in abundance, size frequency relationships and spatial arrangement of dominant benthic organisms and (b) differences in abundance of selected reef fish families. Sampling based on video-belt transects and visual fish counts was carried out along permanent transects in 5 and 10 m depth. Transects were established at six selected reef sites under three different environmental impact regimes, characterised by high terrigenous sedimentation at inner shelf reef sites, fisheries with explosives at outer shelf reef sites and a comparatively low impact of both factors on mid shelf reefs.

The multivariate approach quantified and underlined the distinct differences among the studied reef communities. The results provided insights into the role of community patchiness patterns and question the value of general estimates of live coral percentage cover in initial reef assessments and comparisons among reef sites. The sampling of morphological lifeforms by video belt transects in combination with a visual fish family census proved to be a time and cost efficient tool to gain needed information for the sustainable management of coral reef resources.

"Everything has been visited, everything known, everything exploited. Now pleasant estates obliterate the famous wilderness areas of the past. Ploughed fields have suppressed the forests; domesticated animals have dispersed wildlife. Beaches are ploughed, mountains smoothed, and swamps cleaned. There are as many cities as in former years there were dwellings ..... Everywhere there are buildings, everywhere people, everywhere communities, everywhere life ... we weigh heavily upon the world; its resources hardly suffice to support us. As our needs grow larger, so do our protests that already nature does not sustain us. In truth, plague, famine, wars and earthquakes must be regarded as a blessing to civilisation since they prune away the luxuriant growth of the human race".

(Tertullian, 200 AD)

1. Introduction

Long before early naturalists and marine biologists described the astounding beauty and complexity of pristine coral reefs (Darwin 1842, Hickson 1889, Marsden 1811, Rumphius 1705), tropical coastal communities depended on their rich resources. For them, coral reefs did not only provide food, but also construction material, medicine and jewellery and represented a natural barrier protecting beaches and low islands from wave erosion.

While an increasing number of scientists investigated the biological and geological aspects of reef genesis (Daly 1915, Darwin 1842, Hubbard 1988), the high species diversity on coral reefs (Bellwood 1996, Hubbell 1996, McManus 1985, Veron 1993), as well as patterns and processes related to coral reef ecology (Bak & Povel 1988, Odum & Odum 1955, Sale et al 1994, Stoddart 1969, Stoddart & Yonge 1971), the number of coastal inhabitants in the vicinity of coral reefs increased as well (Jackson 1997). The growing population tended to create a stronger pressure on reefs and other coastal ecosystems, mainly through higher food demand, pollution, a greater need for construction material on coral cays and low islands and by ongoing migration to unsettled shores and islands (McManus 1997).

The human impact on ecological processes on coral reefs and the human dependence on coral reef resources did not become a major scientific issue until the late 1970's. In a summary of problems and prospects in reef studies regarding regional variation in Indian Ocean coral reefs in 1971, conceptual problems in coral distribution studies and the operational problems in recording local variability on reefs during field surveys were considered to be the main challenges for future reef studies (Stoddart & Yonge 1971). Only two decades later impacts of increasing land-based sedimentation and pollution, over-exploitation of reef resources and the use of destructive fishing methods as well as questions regarding applied research for sustainable reef management and coral reef conservation had become additional main issues among coral reef scientists (Ginsburg 1994, Richmond 1993).

Acknowledging the growing importance of assessing and interpreting human impacts on coral reefs, it was the objective of the present study, to characterise and compare coral reef communities under different environmental impact regimes on the coastal shelf of West-Sumatra. The selected reefs showed high terrigenous sedimentation at inner shelf reef sites, physical disturbance caused by fisheries with explosives on outer shelf reef sites and a comparatively low impact of both factors on mid shelf reefs.

The following introductory chapters will lead to the selected approach by briefly reviewing the ecological and economical value of coral reefs (Chapter 1.1) in contrast to environmental impacts, which are increasingly endangering the functional integrity of coral reef communities (Chapter 1.2). A short summary of current approaches in the assessment of benthic reef communities (Chapter 1.3) will be followed by the specific frame and objectives of this study (Chapter 1.4), highlighting the central questions and the chosen approach.

1.1 Coral Reefs: Ecological and Economical Resource Value

The general perception of coral reef ecosystems has changed markedly during the last two decades. Growing awareness of the important ecological and economical role of global coral reef resources is paralleled by a strong increase in evidence for widespread reef degradation (Brown 1988, Brown 1997, Hodgson 1997, Wilkinson et al 1994). This statement is underlined by the fact that half of the world's coastlines are situated in the tropics and about a third of the tropical coastlines are lined by coral reefs. They represent one of the most biologically productive ecosystems world-wide. Two decades ago, the global potential for **coral reef fisheries** has been estimated at 6 million tons per year, or in other terms about 7% of the total marine fisheries of the world (Munro 1984, Smith 1978), while Longhurst and Pauly (Longhurst & Pauly 1987) calculated a yield of 0.48 million metric tonnes for 1983. More recent data compilations tend to be site specific and document yields ranging from 0.4 to 36.9 t km^{-2} $year^{-1}$ (Arias-Gonzales et al 1994).

Apart from benefits through subsistence and commercial fisheries, reefs provide various other values. Marine tourism including **SCUBA - diving** plays an increasing role in the economies of tropical developing countries and the rapidly growing **trade with ornamental fishes and live corals** operates in the tens of millions of dollars annually. Coral skeletons and molluscs are objects of a still growing **jewellery and curio trade**, while sea weeds are collected and cultured on coral reefs, providing **food, fertiliser, medicaments** and industrial base products such as agar or carrageenan. Coral limestone in form of rubble or sand is still widely used for **building materials**, breakwaters and cement.

Based on the greatest biological diversity per hectare of any marine ecosystems in terms of phyla and classes (Birkeland 1997), the potential for **pharmaceuticals** from natural reef products is immense. Indirect effects such as the food supply for more wide-ranging and economically important pelagic fish species, the **protective function against wave action** in comparison to the costs of building and maintaining equivalent breakwaters or the stabilising effect of reefs on the social structure of coastal human communities are examples for further, often unperceived benefits.

In addition, it is increasingly acknowledged that ecosystems such as coral reefs contain various intrinsic "values" without direct human benefits, e.g. represented by complex interspecific feedback mechanisms or large scale ecosystem interactions.

1.2 Coral Reef Degradation

A comparison and evaluation of 63 case studies in 1993 provided insights in the role and hierarchy of major hazards to coral reefs (Ginsburg 1994). Among 42 identified reef hazards, the increasing rates of terrigenous sedimentation and pollution as well as destructive fisheries and overfishing proved to be the most important factors in the process of reef degradation.

Sediment particles smother reef organisms and reduce photosynthetically active radiation. Heavy sedimentation has been associated with fewer coral species, less live coral, lower coral growth rates, greater abundance of branching forms, reduced coral recruitment, decreased calcification, decreased net productivity of corals, and slower rates of reef accretion (Rogers 1990). Analysis of sedimentation impacts exemplifies the difficulties in the separation between natural and anthropogenous disturbance impacts. Soil erosion and transport of

sediment into coastal marine ecosystems have been natural processes, however soil erosion increased dramatically in recent times due to unsustainable agricultural practices, extensive logging and increased construction and mining activities in coastal areas. It has been shown that rates of erosion increased by as much as 100-fold in the last decades, depending on the type of human activity (Doolette & Magrath 1990). Half the global sediment discharge is entering the ocean from high continental islands in the tropical western Pacific (e.g. Papua New Guinea, Philippines, Indonesia) and additional 25-30% from Southeast Asia (Milliman 1992). Hence, the locations of maximum sedimentation coincide with the area of greatest diversity in coral reef communities.

Increased sedimentation and nutrient input into coastal marine ecosystems have also been related to natural phenomena, such as toxic dinoflagellate blooms (MacLean 1984) and large scale population outbreaks of animals with planktotrophic larvae (Birkeland & Lucas 1990). Increased nutrient input may cause increased densities of phytoplankton, bacteria and organic matter, benefiting the larvae of different key species, such as the corallivorous sea star *Acanthaster planci*. As an additional anthropogenous factor, overfishing of predators of invertebrate grazers might be of importance in relation to grazer population outbreaks and following mass mortality, when grazer populations grow beyond the capacity limits of their food resources (McClanahan 1995, McClanahan et al 1996). Similar to population outbreaks of *Acanthaster planci* in the Pacific, mass mortalities of the sea urchin *Diadema antillarum* in the Caribbean shifted reef communities from coral to algal dominance over large areas and long time periods (Carpenter 1997, Carpenter 1990a, Carpenter 1990b).

Commercial coral reef fisheries with high yields seldom proved to be sustainable and the subsequent **over-exploitation** often caused substantial changes in community compositions (Craig et al 1995, Craig et al 1993, McClanahan 1995). **Destructive techniques**, such as fishing with explosives or toxic substances as well as other illegal reef fishing methods like the Muro-Ami ("mouth of death") nets in the Philippines aim for fast, non-sustainable yields. Over the last decades they have destroyed extensive reef areas .

During geological times, coral reefs have encountered severe **natural disturbances** such as hurricanes or tidal waves, which caused periodical community shifts. In contrast, recent anthropogenous impacts seem to increase continuously in scale and frequency, causing chronic stress rather than acute impact scenarios. In order to study and evaluate human and natural impacts reliably, baseline data of unaffected reefs are essential. However, recent publications (Birkeland 1997, Jackson 1997) stressed the fact that scientists tend to be biased, since they have been trained in substantially altered coral reef ecosystems. Hence, they usually have to take the already altered state as a baseline against which reefs are judged to be "normal". In this context it is important that impact assessment of identified disturbance factors within a restricted spatial area is accompanied by more extensive reef community assessments to provide baseline data for future large scale comparisons.

1.3 Approaches in Coral Reef Community Assessment

Assessment of reef communities is complex, due to a variety of reasons. The usually steep vertical gradients related to decreasing wave impact and photoactive radiation with increasing depth cause the formation of narrow bands of comparable reef communities rather than extensive homogeneous assemblages (Bak 1977, Done 1983, Loya 1972). In addition, the horizontally varying exposure to wind and waves as well as to natural and anthropogenous disturbance regimes further modifies these community belts. Combined with the intrinsically high diversity of reef ecosystems, these factors often lead to reef communities of complex spatial patchiness within tens or hundreds of metres (Done 1983).

Slow growth rates and long life spans characterise most scleractinian corals, the main structuring agents in benthic reef communities. These factors maintain small scale patchiness, since succession processes after disturbances may extend over several decades (Done 1986). Such a time period exceeds the life spans of most other reef organisms. Depending on the disturbance regime, the resulting community mosaics may be of different functional value regarding organic production and net reef growth (Pichon 1981).

In view of the complexities of benthic coral reef community patterns, it is not surprising that a variety of scientific assessment techniques on different spatial scales has been described to date (for reviews see English et al., 1994; Rogers et al., 1994; Stoddart and Johannes, 1978). Remote sensing (Mumby et al 1997) and aerial photography (Hopley 1978, van Duyl 1985), covering tens of square kilometres of reef habitat are followed on a smaller scale by the linear manta tow technique (Done et al 1981), which is analogous to a low altitude flight over vegetation on land. Different transect techniques over tens of metres (Carleton & Done 1995, English et al 1994, Loya 1978) and quadrate cover techniques on a range of square metres (Bak & Engel 1979, English et al 1994, Pichon 1978, Scheer 1978) finally represent the smallest assessment scale.

Compared to early studies of coral reef communities, which focused on general biological and geological patterns and processes, more recent research additionally tends to address practical needs in reef resource management and conservation. Interdisciplinary questions regarding socio-economic needs and cost-benefit analysis in relation to sustainable management of coral reef resources document a shift in public attitude (Spurgeon 1992).

Early collections of field research techniques for coral atoll expeditions and reconnaissance studies (Fosberg & Sachet 1953) were followed by a monograph with quantitative methods of measuring and recording ecological data (Stoddart & Johannes 1978). In response to the persisting need for standardised approaches the Australian Institute of Marine Sciences (AIMS) developed and suggested a number of standard assessment and monitoring methods for benthic reef communities over the past two decades. Ranging from broad scale to fine scale, the main survey methods employed by AIMS can be grouped in seven categories (De Vantier & Done 1995):

- Manta-towing
- Survey-swims, visual or video
- Line-intercept transects
- Belt-transects, visual or video
- Stereo-photo quadrates
- Mapping with trilateration
- Coral settlement plates

The early emphasis on standardised reef assessment methods for impact analysis and reef resource management (UNESCO 1984) might have been counterproductive in so far as, contrary to the recommendations of AIMS, only few methods have been added to the standard sampling protocols in various tropical countries. As an example, training courses and sampling programmes for reef survey and monitoring often focus on the "Line Intercept Transect" technique (LIT) to obtain quantitative estimates of benthic cover and composition. Although LIT data in appropriate sampling designs are suitable for both univariate (Mundy 1991a, Mundy 1991b) and multivariate analysis (Reichelt & Bradbury 1984), their evaluation and interpretation often suffers from several deficiencies:

1) Insufficient replication within and between sampling sites and inappropriate sampling design, mainly due to underwater time constraints
2) Misleading interpretation based on comparisons of live hard coral cover only (0-25 % live cover are often supposed to indicate poor reef condition, 25-50 % fair, 50-75 % good, 75-100 % excellent)
3) No data collection regarding coral colony size
4) Exclusion of important additional factors, such as habitat and substrate type, from assessment and analysis approaches
5) Non-standardised selection of reef habitats for LITs. Therefore often inappropriate comparison of cover data for different reef types and reef habitats, due to insufficient or incongruent working definitions of reef types

A major advantage of the "**Line Intercept Transect**" technique is the use of "lifeform categories" (Bradbury et al 1986), which enable non-specialist field-workers to collect quantitative field data on benthic community composition without specialised field equipment. Since this method is also part of the "ASEAN-Australia Marine Science Project", many recent reef surveys in Southeast Asian countries carry out reef assessments based on LITs.

During the last decade, video cameras in underwater housings have become more compact and provide improved resolution under low light conditions. **Underwater video** has so far been applied for mapping and quadrate photography, quantitative surveys, time lapse video and water flow measurements (Maney *et al.*, 1990). The improvement of "video transect" methods bears the potential to avoid the mentioned disadvantages of LITs, while utilising the lifeform category approach. Video-belt transect methods are therefore increasingly used in monitoring and impact assessment studies on the Great Barrier Reef and in other reef regions (Christie & Mapstone 1994, Vogt 1995). Since the relative proportions of different benthos categories sampled by a random point sampling method provide an unbiased estimate of their percent cover, the results are comparable with data gained by the "Line Intercept Transect" technique (Carleton & Done 1995, Vogt 1995). Video-belt transects additionally provide a permanent visual record of the area surveyed.

In the frame of integrated reef assessments, **reef fish abundance** data provide important baseline information regarding the state of the primarily harvested reef resource. Reef fish abundance not only depends on fishing pressure and food supply, but also on surface topography (Grigg 1994, Luckhurst & Luckhurst 1978, McCormick 1994) , which can be significantly altered by terrigenous sedimentation and blast fishing. Visual fish counts along belt transects are a commonly used standard method for assessing fish abundance (Oliver et al 1995) and can be efficiently combined with line or belt transects for benthic community assessment.

1.4 Objectives of the Study

To analyse and evaluate the structure of different reef communities on the coastal shelf of West Sumatra, sites under three different environmental regimes were chosen. Based on previous investigations(Kunzmann 1997, Kunzmann & Efendi 1994), the selected sites differed in regard to:

(a) impact of high terrigenous sedimentation at inner shelf reef sites,
(b) physical disturbance caused by fishing with explosives at outer shelf reef sites and
(c) a comparatively low impact of both factors on mid shelf reefs.

Since terrigenous sedimentation and fishing with explosives are known to be major degrading factors, it was of central interest to analyse in how far reef communities in similar habitats would differ under impact of the different regimes:

- Are single selected community parameters sufficient to differentiate among the different impact regimes?
- Is it possible to discriminate among different reef sites by using multivariate groups of community parameters to obtain low dimensional relation patterns?
- In how far do results of benthic community assessments vary, depending on the commonly chosen depth horizons of five and ten metres?
- How does the locally high patchiness of the benthic communities influence the results for the selected parameters?
- In which respect does the reef fish community reflect the results of the benthic community assessment?

Regarding the mentioned shortcomings in commonly used reef assessment methods, this study included a strong methodological component by adapting video-belt transects and visual fish counts for quantitative sampling. A variety of reef community parameters were selected to be assessed and analysed. These included (a) differences in abundance, size frequency relationships and spatial arrangement of dominant benthic organisms (Table 3.2.1) and (b) differences in abundance of selected reef fish families (Table 3.4.1).

Table 1.1 Overview of approach and methodology (methods marked with asterisks were carried out in the wider frame of this study and will be published independently).

Investigated Aspect	Methodology
1. Initial Extensive Reef Survey	"Manta Tow" Mapping *
2. Benthic Reef Community Assessment	a) Video -Belt Transects
	b) Artificial Settlement Substrates *
3. Reef Fish Community Assessment	Visual Fish Counts

Potential "indicators" for degraded reef communities were additionally analysed based on the video transects. These include size-frequency relationships of hard corals, the abundance of displaced or fragmented coral colonies in comparison to corals in growth position and the occurrence of lesions in coral tissues. All investigations were carried out along replicated permanent transects, which were established at six sites, including two selected reef sites under each of the three different environmental impact regimes.

In regard to reef fish abundance, it was the objective to detect and describe spatial abundance patterns among the selected reefs based on abundance of single families as well as by adopting multivariate methods for groups of fish families. These patterns were compared with the results of the benthic community assessments. It was of further interest, whether the taxonomic aggregation on family level would reveal distinctive differences among the different environmental impact regimes.

2. Methods

2.1 Site Selection

Since only few geomorphological or ecological data are available concerning coral reefs in the area (reef structure investigations of two reef sites in the bay of Teluk Bayur (Umbgrove 1931); "manta tow" and "LIT" data (Kunzmann & Efendi 1994) eighteen reef sites in the vicinity of Padang were visited prior to the selection of reef sites for permanent transects.

General geomorphological patterns, potential impact by sedimentation and fisheries with explosives or toxic substances as well as common compositions and distributions of benthic communities in relation to dominant wind-wave and swell exposure were observed and noted as part of a broad scale survey .

Two geographically and geomorphologically distinct groups of islands and reefs in the study area were differentiated and accordingly designated as cross-shelf sector I and cross-shelf sector II (Fig. 2.1). Although no core drilling data are available for West-Sumatra reef systems (apart from reefs in the harbor area of Teluk Bayur (Umbgrove 1931)), different geomorphological features indicate that islands and reefs in sector I are based on carbonate frameworks of biogenic origin, in which scleractinian corals are major framework constituents. Reefs in sector II are usually coastal fringing reefs or fringing reefs around high island foundations of volcanic origin. According to the geomorphological nomenclature (Guilcher 1988, Hopley 1982), six main reef types occur in the area: (1) vegetated coral cays, (2) submerged bank reefs, (3) submerged patch reefs, (4) patch reefs with vegetated sand cays, (5) high island fringing reefs and (6) coastal fringing reefs.

Sector I

P. Bando (P.= Pulau (indon.): island), P. Pieh , P. Pandan, P. Toran and formerly also P. Laut are vegetated coral cays on Holocene reef deposits and as such constituents of a northward extending drowning barrier reef on the shelf edge of West Sumatra. According to local fishermen, the formerly vegetated sand cay P. Laut was covered by tree and shrub vegetation until about 1987, when increasing erosion of the reef platform (apparently due to intensive fishery with explosives) allowed waves and swell to wash over the entire island. No remains of vegetation were left, when the sand cay was visited in 1995.

Other vegetated coral cays are often interspersed with submerged bank reefs, such as Kg.-Kg. Dorothea (Kg.-Kg.= plural of "karang" (indon.): coral, submerged reef), Kg. Bellona, Kg. Laut and Kg. Condor, which are also constituents of the mentioned barrier reef system. On the shelf or referring to the barrier reef in the lagoon between the reefs mentioned above and the coast of West Sumatra patch reefs of different size are found, with and without sand cays.

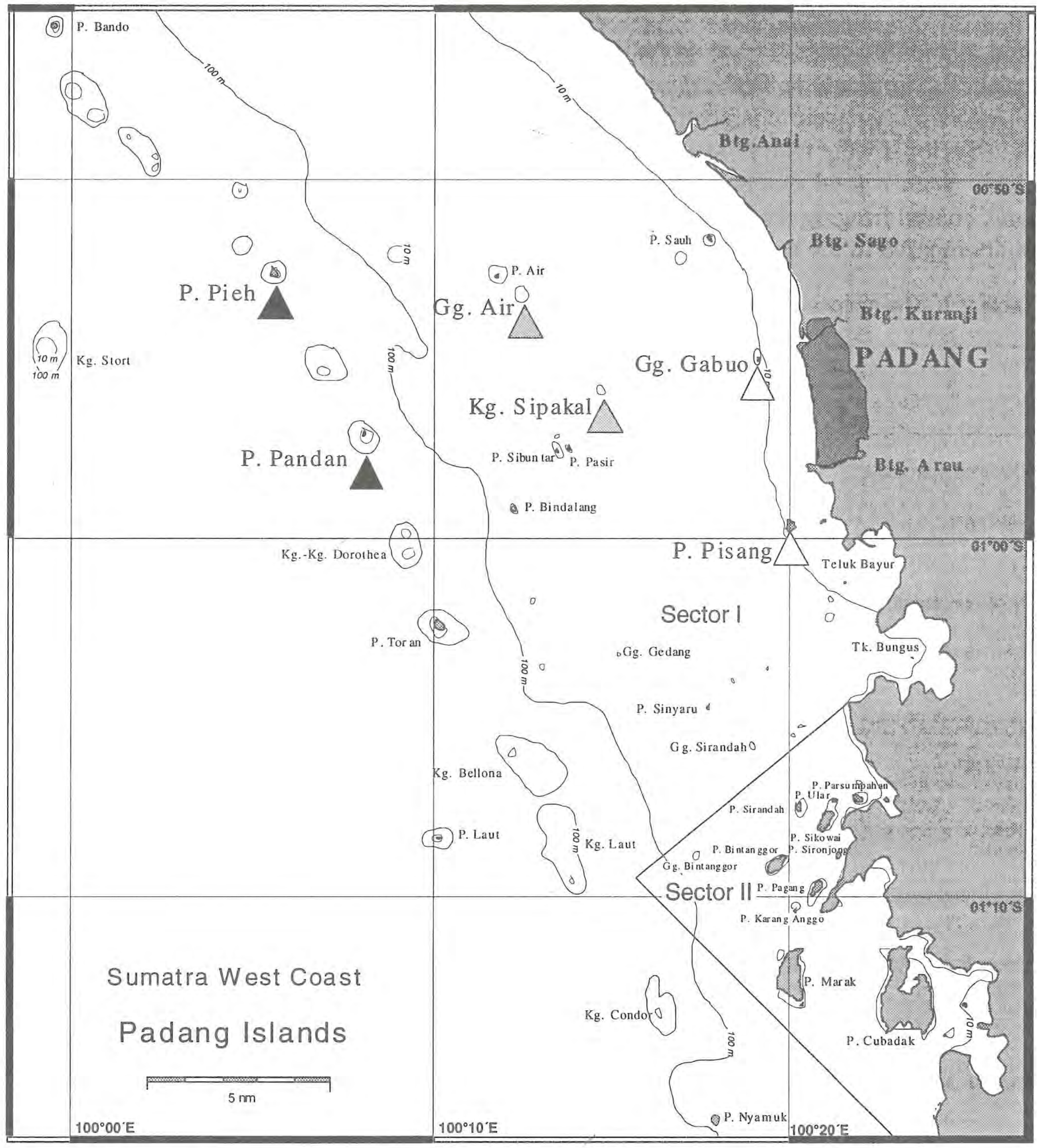


Fig. 2.1 Map of Padang islands. Triangles mark selected study sites in inner shelf (white), mid-shelf (grey) and outer shelf (black) position (Map modified after Kunzmann and Zimmermann, 1994).

Gg. Air (Gg.= "Gosong" (indon.) submerged reef, usually used for shallow submerged patch reefs) , Gg. Sao, Gg. Sipakal, Gg. Gabuo, Gg. Gedang, Gg. Sirandah and Gg. Bintanggor are examples for submerged patch reefs in sector I. These reefs do not have associated sand cays, since waves pass over the reefs without refraction, so that reefal sediments are usually deposited evenly. P. Sauh, P. Air, P. Sibuntar, P. Bindalang, P. Sinyaru and P. Pasirgedang are patch reefs with vegetated sand cays. P. Pisang is an exception in sector I in so far, since it is a high island with an associated fringing reef. Coastal fringing reefs are only found in sector I along the bays of Teluk Bayur (Fig. 2.1) and Teluk Bungus.

Sector II

Visited islands in cross-shelve sector II, such as P. Parsumpahan, P. Ular, P. Sikowei, P. Sirandah, P. Sironjong, P. Bintanggor, P. Pagang, P. Karang Ango, P. Marak, P. Cubadak and P. Sironjong Besar were characterised as fringing reefs around high islands. Coastal fringing reefs in Sector II were mainly found along the bays T. Sungai Pisang, T. Sungai Pinang and T. Tarusan. With a total extent of over 41 km in length in the south of the province capital Padang, coastal fringing reefs are an important reef resource in the study area of equal spatial extent compared to the reef types mentioned above.

Table 2.1 Geomorphology and disturbance regime of southerly sites at the selected reefs.

	Gosong Gabuo	Pulau Pisang	Karang Sipakal	Gosong Air	Pulau Pieh	Pulau Pandan
Distance from coast	1.5 km	2 km	11 km	12 km	21 km	23 km
Reef type	shallow submerged patch reef	high island fringing reef	submerged patch reef	submerged patch reef	vegetated sand cay	vegetated sand cay
Maximum depth	11 m	17 m	80 m	100 m	300-1000 m	300-1000 m
Max. depth with live hermatypic coral	6 m	10 m	40 m	40 m	60 -70 m	60-70 m
Southern slope angle	25 - 35°	30 - 40°	35 - 45°	40 - 45°	40 - 45°	40 - 45°
Turbidity [mean Secchi-disc depth]	2 m	4 m	15 m	22 m	22 m	24 m
Relative terrigenous sediment impact	very high	high	low	very low	none	none
Wave and swell impact at southerly site	medium	medium	high	high	high	high
Mean bomb pit density on reef crest [n (500 m)$^{-2}$]	1	0	0	1	5	8

Selected Sampling Sites

Within the limits of employed methods, logistics and costs, the following setup of sampling sites was developed. Six of the 18 visited reefs were selected in three different cross-shelf positions between the coast of West Sumatra and the shelf edge. In order to assess differences in (a) abundance, size frequency relationships and spatial arrangement of dominant benthic organisms and (b) differences in abundance of selected reef fish families in relation to different environmental impact regimes, the set-up of permanent transects included three spatial levels:

1. Three pairs of reefs under similar environmental impact regimes in comparable cross-shelf position
2. Two different reef habitats- reef crest and reef slope- in comparable reef sectors of each reef
3. Five permanently marked 50 m long transects parallel to the isobath within each habitat at each reef site

Hence a minimum of two reefs per shelf-position allowed also comparisons between reefs under fairly similar environmental impact regimes. The high island fringing reef P. Pisang and the submerged patch reef Gg. Gabuo, are lying on the inner shelf in about 1.5 km distance from the shore of West-Sumatra. The submerged patch reefs Kg. Sipakal and Gg. Air are lying on the mid-shelf about 11 km offshore and the vegetated sand cays P. Pieh and P. Pandan are situated about 22 km offshore (Fig. 2.1).

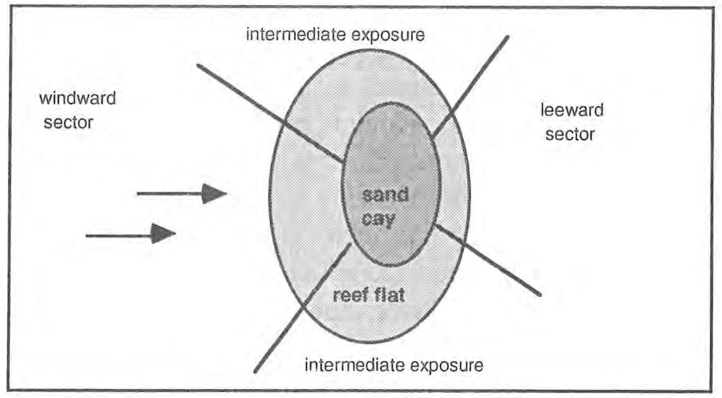


Fig. 2.2 Simplified scheme of reef exposure to wave impact.

At each reef a southerly site of intermediate exposure to wind waves and swell was selected. Due to strong differences in wave impact and sedimentation pattern, benthos communities on windward and leeward reef sites were generally more different from each other, than the communities in the two reef sectors with intermediate exposure to wave impact.

Both extremes of exposure were characterised by lower numbers of species and dominance of fewer, adapted species. Sampling of either of them was therefore considered less representative for the entire reef than the assessment of one of the two remaining reef sectors, since these represent about 50% of comparable reef area (Fig. 2.2).

2.2 Permanent Transect Establishment

In order to resolve the potentially different impacts of fishing with explosives and terrigenous sedimentation on reef crest and reef slope communities separately, transects were established in two depth zones. Five transects were randomly located on the reef crest in 5 m depth in about 5-10 m distance from the reef edge and five transects were established on the shallow reef slope in 10 m depth. Tape measures of 50 m length were used to establish the transects at each site, before aluminium poles and iron rods were cemented into the reef pavement in 10 m intervals to designate each permanent transect. Tape measures were laid out again at each survey occasion to mark the transect path.

2.3 Benthic Community Assessment

2.3.1 THE UW-VIDEO-SYSTEM

The SONY CCD-VX1E video camera used for the video belt transects is a high resolution camcorder. With a minimum illumination limit of 4 lux the system provided sufficient brightness and colour reproduction capabilities under difficult light regimes. The system employs small 8 mm video format cassettes (HI8 or standard 8 mm) with a recording time of 1 hour 30 min in SP mode and 3 hours in LP mode. A low power consumption of 9.4 W during recording allows more than 80 min constant recording under field conditions with commercial SONY NP-90 battery packs. The camcorder includes an independent playback and editing unit with high still picture quality in "Pause" mode, which is essential for video analysis under field conditions. During video analysis the permanent RC time code indicates the absolute position of the tape with hour, minute, second and frame while a data code provides date and time of recording. Both codes are allowing indexing and archiving of data sets. The camcorder was used in an " AMPHIBICO " underwater housing, which provided electronic remote control options for camera settings, such as white balance, aperture, shutter, gain and setting of the ND (Neutral Density) filter. For video transects a wide angle lens and a dome port on the camera housing provided a maximum depth of field. A red-filter (AMPHIBICO-Products) was used in order to increase colour saturation to facilitate identification of benthic organisms during video analysis in the laboratory.

2.3.2 FIELD SAMPLING

Each transect was filmed twice per survey. During a "**video habitat transect**" (VHT) the diver was swimming 2.5 m above the substrate following the transect with the camera pointing diagonally downward in an angle of about 45°. The VHT provided a perspective of 20 m width (depending on the visibility) as background information for the analysis of the narrow "video belt transects" (VBT). Questions regarding different topographic features, such as density of bomb pits, spoor and groove systems, vertical topographic heterogeneity and extent of community distribution patterns could therefore be determined and described when necessary in addition to the results of the narrow VBTs.

The narrow "**video belt transects**" (VBT) were carried out swimming 0.5 m above the 50 m long measuring tape. In order to allow size estimations of benthic organisms and to keep errors due to varying distances between camera and substrate at a minimum, an aluminium frame was attached to the camera housing. The frame marked a substrate area of 40 cm width and 25 cm height (1000 cm^2, see Fig. 2.3). The average distance between frame and substrate measured 5 to 10 cm depending on substrate morphology.

An average swimming speed of 10 m min^{-1} proved to be the best compromise between resolution of the still video picture for analysis and swimming efficiency under varying environmental conditions, such as swell or current.

2.3.3 VIDEO ANALYSIS

Abundance of corals and other lifeform categories was estimated using a point sampling and a belt sampling method. While the video tapes of the transects were played back for the first time on a 21 inch TV monitor, certain "macro invertebrates" (mushroom corals, sea anemones, soft corals, gorgonians, crinoids, holothurians, sea urchins, sea stars, molluscs, sponges) were counted in the entire belt transect of 0.4 m by 50 m (20 m^2). Pilot studies revealed that 50 video stops (equivalent to one stop per metre reef substrate along the belt transect) and sampling of five sampling points per video stop (resulting in 250 data points per transect), were most efficient for the sampling approach. Higher numbers of video stops or points per video stop did not provide significantly higher accuracy.

The sampling points were initially assigned randomly in one central and four lateral screen sectors of the same size and marked on the screen (Fig. 2.3). In order to compensate variations in swimming speed along the transect due to current or swell, the absolute time span of every transect video sequence was measured and divided by the number of required video stops to calculate the length of intervals between video stops in seconds for calibration. Regular pauses combined with fixed point placement results in *regular linear point sampling* in the present study in comparison to *random point sampling* (random pauses and repeated random point placement, (Carleton & Done 1995) and random pauses combined with fixed point sampling resulting in *random linear point sampling* (Ohlhorst et al 1988).

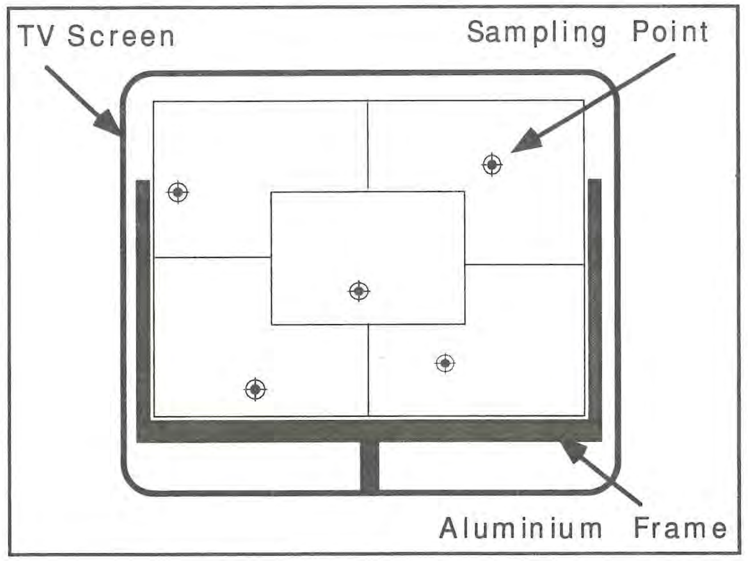


Fig. 2.3 Setup for regular linear point sampling.

Similar to the Line Intercept Transect technique (LIT) lifeforms and substrates under random points were analysed using a classification system based on structural attributes of lifeforms rather than species level data (De Vantier 1986). Occurrence of reef substrate categories under random points at every video stop were directly entered into a relational PC data base. Substrate categories and parameters were entered using menu-based fields in a programmed sampling mask with 37 potential parameters on three categorical levels, a) benthic group, b) benthic lifeform and c) further scleractinian coral variables. Benthic lifeform categories were named according to the commonly used nomenclature (English et al 1994). Table 2.2 lists all parameters, which were assessed during analysis of the video belt transects.

Table 2.2 List of categories and abbreviations used in the analysis of video belt transect data (partly adapted from (Christie et al 1995).

CATEGORY 1	CODE	CATEGORY 2	CODE	CATEGORY 3	CODE
BENTHIC GROUP	BG	BENTHIC LIFEFORM	BLF	ECOLOGICAL VARIABLES	EV
Reef Rock	RP	Abiotic	AB		
Rubble	R				
Sediment/ Rubble	SR				
Fine Sediment	S				
Live Hard Coral	LC	Live Hard Coral Growthform: Acropora branching Acropora tabulate Acropora digitate Acropora encrusting Coral encrusting Coral foliaceous Coral branching Coral Mushroom (Fungiidae) Coral massive Coral submassive	 ACB ACT ACD ACE CE CF CB CMR CM CS	Coral Genus Maximum Diameter Colony in Growth Position Colony Displaced Colony Fragment Lesion	 MD GP ColD ColF L
Dead Hard Coral	DC			Dead Coral Growthform: (same as for Live Coral) Maximum DC Diameter Dead Coral Colony White Dead C. Col. with Algae Displaced DCW Displaced DCA	 MD DCW DCA DDCW DDCA
Sponge	SP	Sponge	SP		
Soft Coral	SC	Soft Coral	SC		
Macro Algae	MA	Macro Algae Turf Algae Coralline Algae	MA TA CA		
Others	OT	Heliopora, Gorgonaria, Millepora, Actiniaria, Anthipatharia, Zoanthidea, Mollusca, Holothuria, Crinoidea, Asteroidea, Echinoidea	OT		
Indeterminate	IN		IN		

The designation of "benthic groups" and "benthic lifeforms" followed the approach of the long term monitoring project of the Australian Institute of Marine Sciences on the Great Barrier Reef (Christie et al 1995). Although these terms can cause misunderstandings, since they may not be intuitively differentiated, they were kept for comparative reasons.

The "benthic group" category contains abundant substrates as well as lifeforms, which are major space occupants in reef environments. The "benthic lifeform" category on the other hand includes only the percentage cover of live organisms. The differentiation among the two groups allows to account for the fact that certain substrates can be categorised e.g. as coralline algae or as rubble, depending on the emphasis on lifeform or substrate type. Sampling points were classified as indeterminate, when the respective substrate was not visible, e.g. due to crevices or low light level in shaded areas.

The term abiotic was used for substrates on which no macro-organisms could be detected. The category "ecological variables" includes descriptors for the condition of the scleractinian coral community, namely maximum diameter, state of the live colony (in growth position, displaced or represented by a fragment) and the occurrence of damaged coral tissue areas, for which the term lesion was applied. Similar terms were used to qualify the condition of dead corals. Apart from the maximum diameter, it was noted, whether the respective colony recently died (marked by a still white skeleton), whether it was overgrown by algae, or whether white or overgrown dead colonies were displaced or still in growth position.

Scleractinian corals were identified to genus level when possible. Slight increase of screen colour and contrast levels improved the differentiation between organisms of similar appearance. The sum of random points per category were converted into percentage cover or used directly for descriptive and analytical statistical analysis.

2.4 Visual Reef Fish Census

Visual fish census techniques were first used to count Hawaiian reef fishes (Brock 1954) and have been adopted and modified by many reef ecologists for estimating numbers and biomass of reef fishes (e.g. (Halford et al 1995, Kimmel 1985, Odum & Odum 1955, Parrish 1981, Williams 1986, Williams 1991). In the context of this study the abundance of twelve key reef fish families, 22 common reef fish families and five reef associated pelagic fish families was assessed on all six permanent transect locations (Table 2.3). The distinction among "key" and "common" reef fish families was based on ecological and economical assumptions. Key families include families which (a) include important predators or grazers, (b) generally occur in high abundance, (c) are of commercial value or (d) have been used as indicators in other recent studies (Halford et al 1995).

Three of five permanent transects in 5 m depth were once chosen by random and visually surveyed for the abundance of reef fish families. The 50 m line transects were sampled based on two different belt widths. Fishes bigger than 10 cm were counted on a 10 m wide belt along the transect and within 5 m above the reef substrate. Swimming back after surveying the three chosen transects for bigger fish, the observer recorded fishes smaller 10 cm in a 5 m wide belt, respectively 2.5 m at each side of the transect tape. Distances were estimated visually and verified before and after each transect using the tape measure.

The sampling was carried out between 9:00 a.m. and 4:00 p.m. to minimise sampling variability due to diurnal changes in fish behaviour. Data concerning the presence of a family, the number of different species within one family and the number of individuals were noted on pre-formatted UW-slates.

Table 2.3 List of the surveyed reef fish families and the respective international abbreviations used in the analysis of fish census data.

Common Families	Code	Key-Families	Code
Apogonidae	APOG	Acanthuridae	ACAN
Aulostomidae	AULO	Chaetodontidae	CHAE
Balistidae	BALI	Haemulidae	HAEM
Caesionidae	CAES	Labridae	LABR
Centriscidae	CENT	Lethrinidae	LETH
Cirrhitidae	CIRR	Lutjanidae	LUTJ
Diodontidae	DIOD	Pomacanthidae	POCA
Ephippidae	EPHI	Pomacentridae	POMA
Fistulariidae	FIST	Scaridae	SCAR
Holocentridae	HOLO	Serranidae	SERR
Monacanthidae	MONA	Siganidae	SIGA
Mullidae	MULL	Zanclidae	ZANC
Muraenidae	MURA		
Nemipteridae	NEMI		
Ostraciidae	OSTR		
Pempheridae	PEMP	**Reef Related Pelagic Fam.**	
Pinguipedidae	PING	Belonidae	BELO
Priacanthidae	PRIA	Carangidae	CARA
Scorpaenidae	SCOR	Hemiramphidae	HEMI
Syngnathidae	SYNG	Scombridae	SCOM
Synodontidae	SYNO	Sphyraenidae	SPHY
Tetraodontidae	TETR		

Replicate counts at each site were standardised to number of individuals per 500 m^2. Collected data were analysed in regard to (a) general differences in fish family richness, and fish abundance among reef sites, (b) differences in key reef fish family distribution and (c) multivariate analysis of fish family assemblages in relation to geographic location and environmental impact.

2.5 Statistical Analysis

Similarities between the reef sites in terms of benthic group or benthic lifeform composition were examined by non-parametric multivariate methods. Classification and ordination techniques were carried out based on Bray-Curtis similarities (Bray & Curtis 1957) between all replicate transects. The similarity matrix was computed using root transformed substrate cover data, following the recommendations of Clarke and Green (1988) for transformations

and Faith *et al.* (1987) for similarity coefficients. Based on the computed similarity matrix, samples were classified by hierarchical agglomerative clustering with group average linking (Clifford & Stephenson 1975). Subsequently an ordination by non-metric multidimensional scaling (MDS, e.g. Kruskal & Wish 1978) allowed to display samples according to their multivariate similarities in a two-dimensional plot (Fig. 2.4). The "goodness of fit" of the three-dimensional similarity distribution in the two-dimensional MDS plots is quantified by a stress value. If the two-dimensional distances in the MDS plot correspond well to calculated three dimensional similarities, the stress value decreases towards zero. All multivariate computations were performed with PRIMER (*Plymouth Routines in Multivariate Ecological Research*) software developed at Plymouth Marine Laboratory, UK.

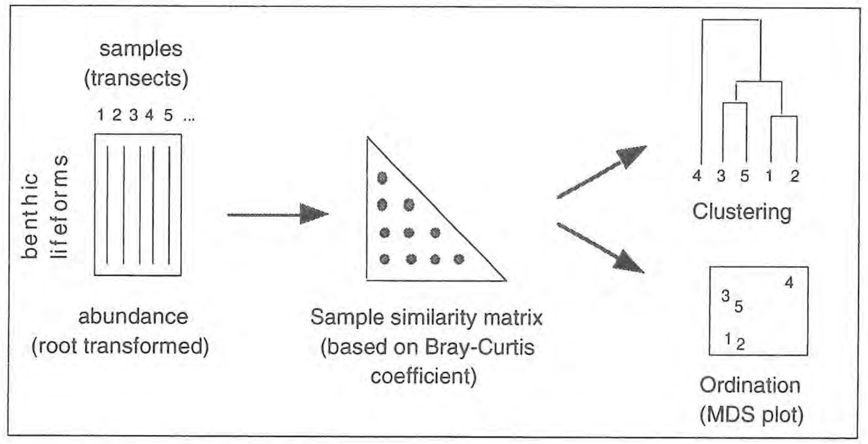


Fig. 2.4 Stages of the multivariate analysis (modified after Clarke & Warwick 1994).

In addition to family richness and fish abundance, fish communities were described by four standard heterogeneity indices (Magurran 1988). These include the Shannon diversity index (H´), calculated as

$$H' = - \sum pi \ln pi$$

where pi is the proportion of the total number of individuals occurring in taxon i.Evenness (E) was calculated as

$$J' = H' / \ln S$$

where S is the total number of species or in this case total number of reef fish families. Simpson's index (D) describes the probability of any two individuals drawn at random from an infinitely large community belonging to different taxa:

$$D = \sum pi\ 2$$

where pi is again the proportion of the total number of individuals occurring in taxon i. In order to account for the finite character of a reef fish community at a given site, the appropriate form

$$D = \sum (ni\ (ni - 1) / N\ (N - 1))$$

was calculated. Since Simpson's D decreases when diversity increases, the index was expressed in comparative graphs as 1-D (Magurran 1988). The Berger-Parker index expresses the proportional importance of the most abundant taxon:

$$d = Nmax / N$$

N_{max} expresses the number of individuals in the most abundant species, while N is the total abundance in a given sample. The index form 1-d was adopted. Therefore an increase in the value of the index indicates an increase in diversity and a reduction of dominance by the most abundant taxon. Analogous to the video belt transects, further analyses were carried out using the multivariate classification and ordination techniques mentioned above.

2.6 Terminology

Clear typology is a prerequisite for comparative coastal studies and management approaches. Especially the term "coral reef" is seldom explicitly defined in scientific studies or in large scale coastal (Crossland et al 1991, McManus 1988, Tomascik et al 1997, van der Land 1989) resource inventories. It is often questionable, whether data on coral reef resources were gathered under comparable geomorphological and ecological circumstances. Reefs in the study area were therefore categorised according to the geomorphological nomenclature (Guilcher 1988, Hopley 1982). The following conventions are supposed to provide a consistent terminology throughout the text.

The term "reef" or the respective reef name, if used in comparisons of reef sites for the sake of brevity, refers to the limited study area on each reef. Generalisations and conclusions drawn from the different data sets are only directly pertinent to the reef crest and shallow reef slope communities at the southerly exposed reef sectors of the chosen locations.

Indonesian names of the studied reef sites were used in tables and figures without the descriptive Indonesian prefixes "Pulau" (island), "Gosong", (submerged reef), and "Karang" (submerged reef) to avoid lengthy expressions.

Since the video-belt transect analysis was using "benthic groups" and "lifeforms" instead of species, the nomenclature followed the standard categories recommended in the "Survey Manual for Marine Tropical Resources" (English et al 1994). The term "hard coral" was used for hermatypic Scleractinia only, not including the hydrozoan genus *Millepora* and the octocorallian genus *Heliopora*. The term soft coral included members of the order Alcyonacea, while Actiniaria (sea anemones), Anthipatharia (black corals) and Gorgonacea (gorgonians) were assessed separately (see Table 2.2). The benthic category "abiotic" was used for substrates without detectable macrobenthos, such as silt accumulations or whitish rubble fragments. The term does not imply the absence of endobenthos or micro-organisms.

For graphs and figures, the conservative differentiation in inner shelf, mid-shelf and outer shelf reef sites was used, since a separation of "sites under impact of terrigenous sedimentation ", "low impact of sedimentation and fishing with explosives" and "impact of fishing with explosives" may have implied the absence of other, potentially interacting disturbance factors. In the text of the results and discussion chapters the following abbreviations were used in addition to the respective reef name to facilitate comparisons:

(I/S) for inner shelf reefs under sediment impact

(M) for mid-shelf reefs under low impact of sedimentation or explosives

(O/E) for outer shelf reefs under impact of fishing with explosives

3. Results

3.1 Composition and Distribution of Benthic Reef Communities

3.1.1 COMPARISON OF HABITATS BY BENTHIC LIFEFORM DISTRIBUTION

Reef crest

The average percentage cover of different benthic lifeform categories is highly variable between reef sites. The mean percentage cover of living macro benthos[1] on the reef crest in 5 m depth ranged from 46% at Sipakal (M= mid-shelf), 65% at Gabuo (I/S= inner shelf under sediment impact), 86% at Air (M) and 91% at Pieh (O/E= outer shelf under impact of fisheries with explosives) to 98% at Pisang (I/S) (Fig. 3.1). No data are included or displayed in the following graphs for the reef crest habitat at Pandan (O/E) due to a technical failure during sampling.

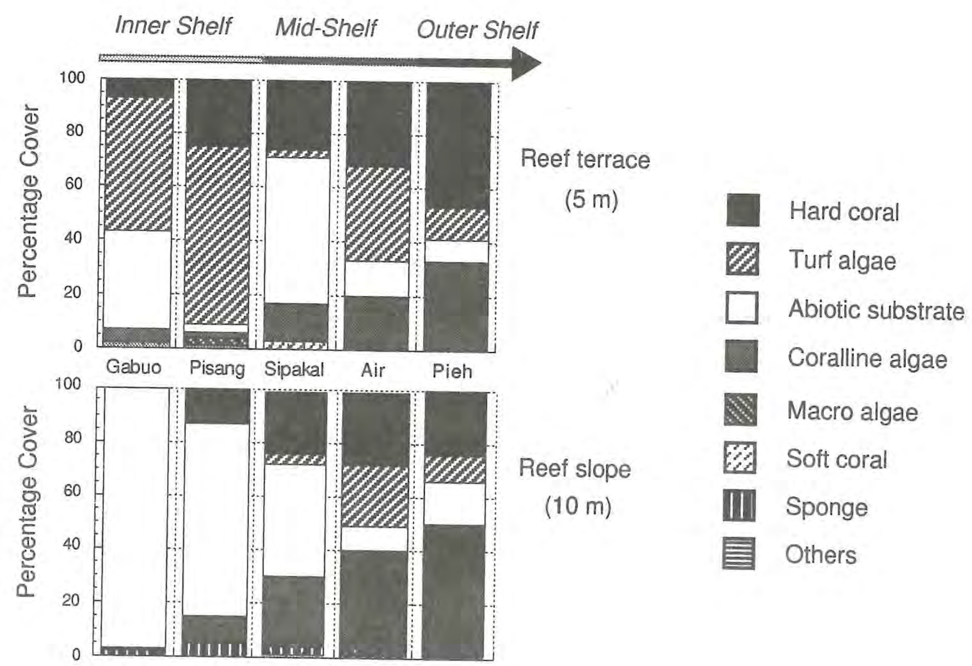


Fig. 3.1 Mean percentage cover of benthic life forms in 5 and 10 m depth.

[1] *Note that the "abiotic" category is not homologous to the combined categories sediment, sediment /rubble, rubble, reef pavement and dead coral (see also Chapter 2.6 and Table 2.2).*

Mean live scleractinian coral cover reached 25% at Pisang (I/S) and Sipakal (M) and 31% at Air (M) with a maximum of 47% at Pieh (O/E) and a minimum of 7% at Gabuo (I/S). Turf algae were abundant at Pisang (I/S) (67%), Gabuo (I/S) (49%) and Air (M) (35%) and less numerous at Sipakal (M) (3%) and Pieh (O/E) (11%). Coralline algae ranged from 2% at Pisang (I/S) to 33 % at Pieh (O/E), while macro algae were only abundant in transects at Gabuo (I/S) (3%). Mean cover of soft corals, sponges and other macro invertebrates did rarely exceed 1%.

Reef slope

Living benthos organisms on reef slopes in 10 m depth were found to have a mean percentage cover of 4 % at Gabuo (I/S), 28% at Pisang (I/S), 58% at Sipakal (M), 82% at Pandan (O/E), 84% at Pieh (O/E) and a maximum of 92% at Air (M). The cover with live scleractinian corals was fairly similar on outer and mid-shelf reefs with a range between 22% (Pandan (O/E)) and 27% (Air (M)), while live coral cover on the inner shelf reef sites reached 1% at Gabuo (I/S) and 14% at Pisang (I/S). Turf algae did not occur in 10 m depth at Gabuo (I/S) and Pisang (I/S) and reached a percentage cover of 8 and 10% at Pieh (O/E) and Pandan (O/E) respectively, 4% at Sipakal (M) and 23% at Air (M). Coralline algae were hardly present on inner-shelf reefs (1% at Gabuo (I/S), 9% at Pisang (I/S)) and reached a maximum cover on the outer shelf reefs Pieh (O/E, 49%) and Pandan (O/E, 51%).

Comparing reef crest and upper slope habitats of the surveyed reef sites, the average percentage cover estimates for benthic lifeforms in Figure 3.1 and Figure 3.2 reveal the following pattern:

- Turf algae, coralline algae and scleractinian corals are the dominant lifeforms in both habitats on the surveyed reefs.
- Mean live scleractinian coral cover on reef crests generally exceeds coral cover on shallow slopes.
- Live scleractinian coral cover was most abundant on the reef crest of the outer shelf reef site Pieh (O/E).
- The majority of remaining reef crest and reef slope stations showed comparable live coral abundance between 20 and 30%, except Gabuo (I/S).
- Turf algae are the most dominant live components on reef crests at Gabuo (I/S) and Pisang (I/S) and are absent on shallow reef slopes of the same reef sites.
- Turf algae abundance decreases on reef crests and increases on upper reef slopes with increasing distance from the coast.
- With the exception of Gabuo (I/S), mean cover with coralline algae on shallow slopes exceeds cover with coralline algae on reef crests.
- Sponges tend to occur in higher abundance on upper reef slopes than on reef crests.
- Abiotic substrate dominates shallow reef slopes on inner shelf reefs and decreases towards the outer shelf, while on reef crests it is generally less abundant and displays no comparable trend.

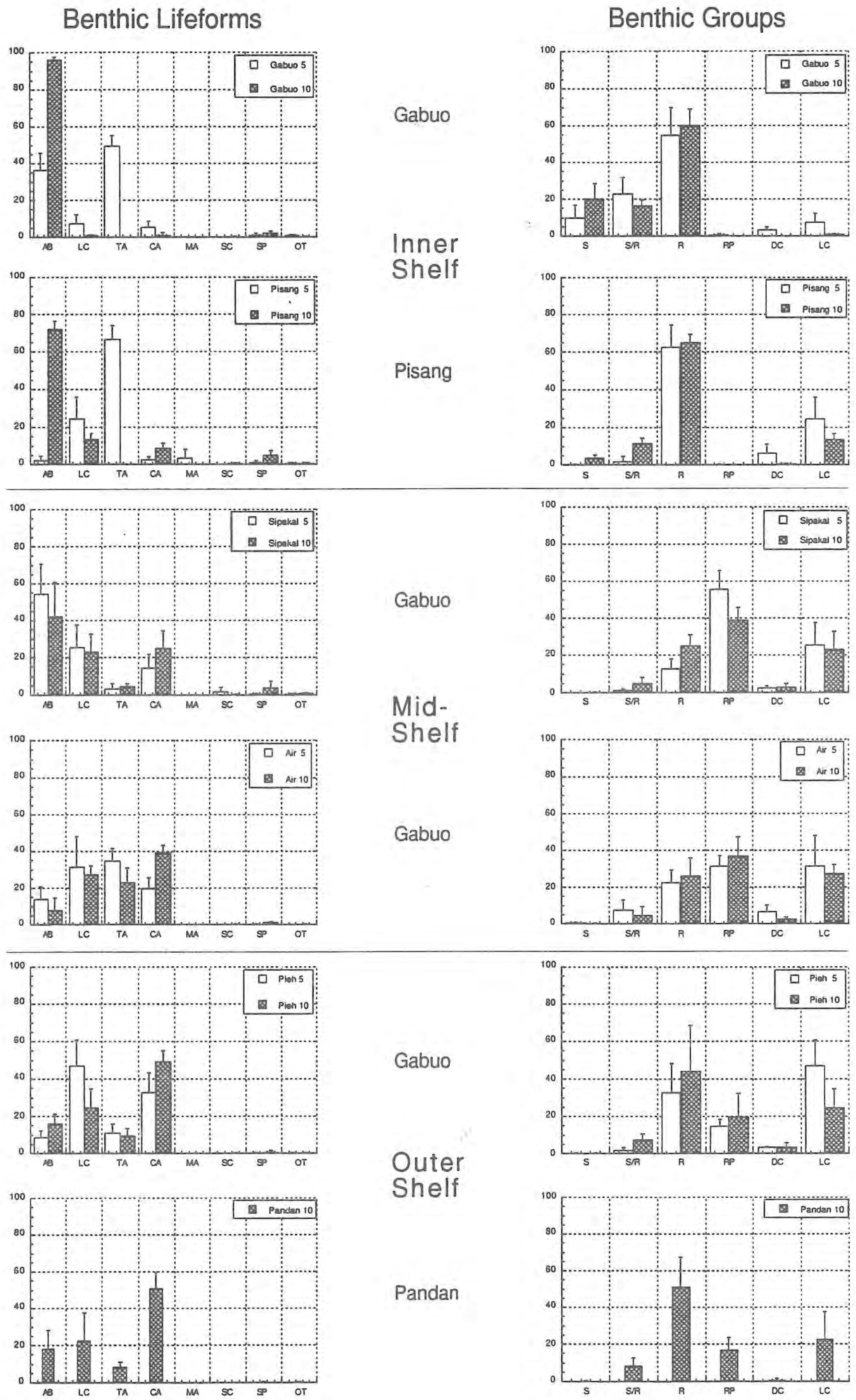


Fig. 3.2 Pairwise comparison of mean percentage cover in regard to "benthic life forms" (left column) and selected "benthic groups" (right column) between reef crest (5 m) and reef slope habitat (10 m). Reefs are plotted in respect to their shelf position. Error bars indicate the standard deviation. AB: abiotic, LC: live scleractinian coral, TA: turf algae, CA: coralline algae, MA: macro algae, SC: soft coral, SP: sponge, OT: others, S: sediment, S/R: sediment/rubble, R: rubble, RP: reef rock, DC: dead scleractinian coral.

3.1.2 COMPARISON OF HABITATS BY BENTHIC GROUP DISTRIBUTION

Reef Crest

Average percentage cover of benthic group categories indicates distinct differences among sites (Fig. 3.2; Fig. 3.3). Sediment is only abundant at the inner shelf reef Gabuo (I/S) (10% cover), while mixed sediment / rubble assemblages were found at Gabuo (I/S) (23%) and at Air (M) (7%).

Rubble dominated the reef crest at the inner shelf reefs Gabuo (I/S) and Pisang (I/S) and was the secondmost abundant category at the outer shelf reef Pieh (O/E), while it reached comparatively little cover at Sipakal (M) and Air (M). Reef rock showed an opposite distribution pattern with high abundance on the mid-shelf reef sites Sipakal (M) and Air (M), lower percentage cover at Pieh (O/E) and minimal cover at Pisang (I/S) and Gabuo (I/S). Dead corals reached only low percentage cover between around three percent at Gabuo (I/S), Sipakal (M) and Pieh (O/E) and six percent at Pisang (I/S) and Air (M).

As already mentioned in paragraph 3.1.1, live scleractinian coral cover showed the lowest value at Gabuo (I/S) (7%) and a maximum cover at Pieh (O/E) (47%). Soft corals, sponges, and "others" hardly exceeded 1%, while macro algae were only found in abundance at Pisang (I/S) (3%).

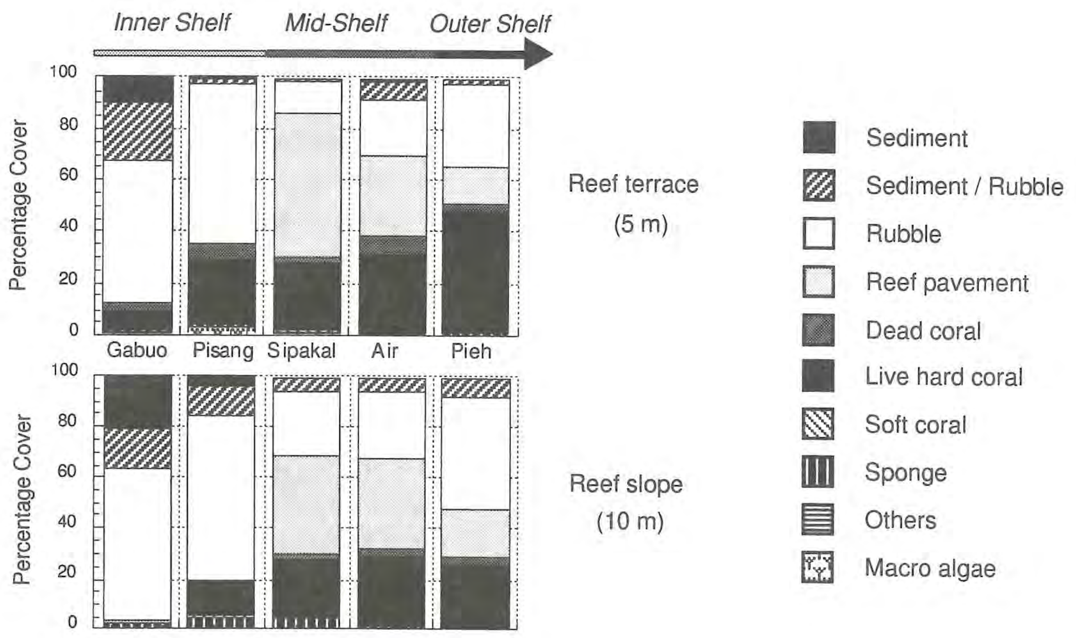


Fig. 3.3 Mean percentage cover of benthic groups in 5 and 10 m depth.

Reef Slope

The data for mean percentage cover of benthic groups on the shallow reef slope (10 m depth) revealed similar distribution patterns as on the reef crest (Fig. 3.3). Sediment cover was only present on the inner shelf reef sites and reached a maximum of 20% at Gabuo (I/S) and 4% at Pisang (I/S). The highest percentage cover of sediment/rubble was found with 12% (Pisang (I/S)) and 17% (Gabuo (I/S)) on inner shelf reefs, while mid-shelf reef sites ranked lowest with 5%, followed by the outer shelf reefs Pieh (O/E) and Pandan (O/E) with 7 and 8% respectively.

All slope habitats were characterised by comparatively high cover with rubble. Inner and outer shelf reef sites were rubble - dominated (44 - 65%) while the mid shelf reefs Air (M) and Sipakal (M) still had a percentage cover of around 25%. Similar to the reef crests, shallow slopes of inner shelf reefs showed no reef rock, while this category ranged around 38% on mid shelf reefs and around 16% on outer shelf reef sites. Dead coral cover of around 3% was found at Sipakal (M), Air (M) and Pieh (O/E), while it reached less than one percent at the remaining sites. Live scleractinian coral cover was similar on mid- and outer shelf reef sites with 22 to 27%. Pisang (I/S) had only 14% of life coral cover, while corals were nearly absent on the shallow slope at Gabuo (I/S).

Soft corals, macro algae and "others" were hardly present, while sponges reached between one and five percent coverage on inner and mid shelf reef sites (Fig. 3.3). Regarding the general distributional patterns of benthic groups, the following trends were observed for surveyed reef crest and reef slope habitats:

- Rubble, live scleractinian corals and reef rock constitute the major space occupants at the surveyed reef sites.
- Sediment coverage was only abundant at inner shelf reef sites, with higher percentage cover on reef slopes compared to respective reef crests.
- Rubble was the most common category and showed generally higher percentage cover on reef slopes than on respective reef crests.
- Reef rock was absent from inner shelf reef sites and reached maximum abundances in mid shelf crest and slope habitats.
- Dead corals were generally rare, with slightly higher percentage cover on reef crests.
- Live coral abundance was similar or lower on reef slopes compared to reef crests.

3.1.3 MULTIVARIATE DISCRIMINATION BETWEEN LIFEFORM ASSEMBLAGES

Results in the previous chapters indicate differences among reef sites based on single benthic categories. Varying relative abundance of e.g. turf algae or variable abundance of scleractinian corals among sites and habitats revealed a complex pattern of differences and trends among reefs. Hence a multivariate approach was selected in order to test, whether the suspected chronic impact of sedimentation and destructive fisheries may be related to general trends in composition and spatial arrangement of benthic lifeform associations. Hierarchical clustering and multidimensional scaling based on a similarity matrix of the multivariate benthic lifeform data, were carried out to discriminate sites and habitats due to similarities and dissimilarities among sampled communities.

Furthermore, pilot studies revealed a distinctive horizontal patchiness of benthic communities at scales of 10 to 20 m parallel to the depth contour lines. Although a transect length of 50 m was chosen to account for the impact of small scale community patchiness, the theoretical possibility existed that differences in benthic community composition among transects at a given reef site might exceed differences among reefs. Two dimensional ordination was used as an exploratory tool to address this question.

Reef crest

In the dendrogram for the reef crest habitat (Fig. 3.5 a) different reefs are clearly distinguished by clusters of similar replicate transects which reflect differing community compositions among reef sites. The cluster pattern goes partly conform with the cross shelf distribution of compared reef sites: The inner-shelf reefs Gabuo (I/S) and Pisang (I/S) together with the mid-shelf reef Air (M) are split by a similarity of S < 44% from the second mid-shelf reef Sipakal (M) and the outer-shelf reef Pieh (O/E). Inspection of the raw data revealed that major differences between the two groups exist in respect to cover with turf algae and coralline algae.

Exceptionally high live coral cover caused the outlier "Air 3" in comparison to other replicate reef crest transects at Air (M) (Air 3: 60% live coral cover, arithmetic mean of live coral cover for the four remaining transects: 24%). The outer shelf reef Pandan (O/E) was not included since the data set for the 5 m crest transects was not comparable due to a technical failure during sampling. The respective MDS plot (Fig. 3.5 b) shows the distinctive differences between groups of transects by means of increasing Euclidean distance as a measure for increasing dissimilarity.

In spite of the clear clustering pattern based on the multivariate data sets, the comparison of single benthic lifeform categories between replicate 50 m transects in 5 m depth showed the expected high variance in abundances. Live coral cover for example ranged at Pisang (I/S) between 9 and 38%, at Gabuo (I/S) between 0 and 13%, at Sipakal (M) between 9 and 38%, at Air (M) between 18 and 60% and at Pieh (O/E) between 36 and 70% (Fig. 3.4).

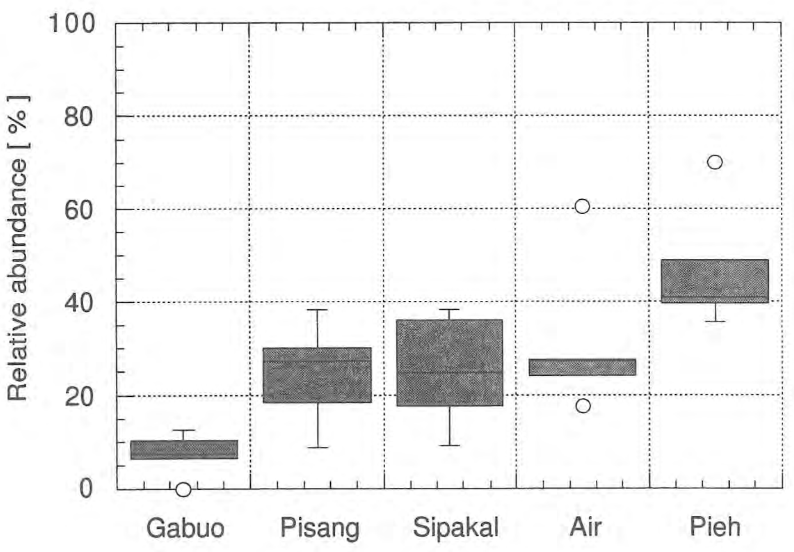
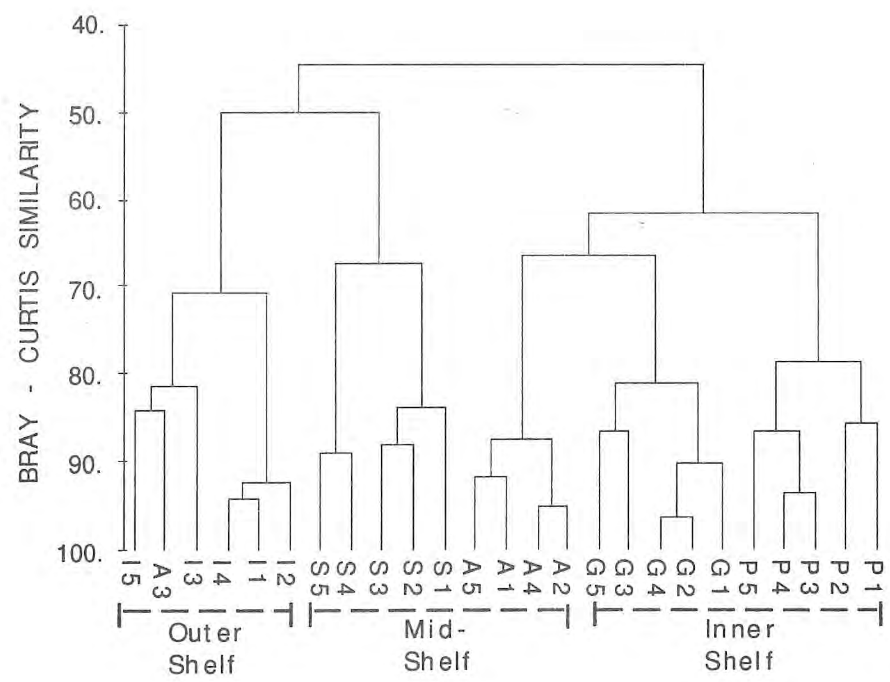


Fig. 3.4 Relative abundance of live scleractinian corals on reef crest transects (5 m). The box and whisker plot indicates variability among 5 replicate transects within each reef site.

a



b

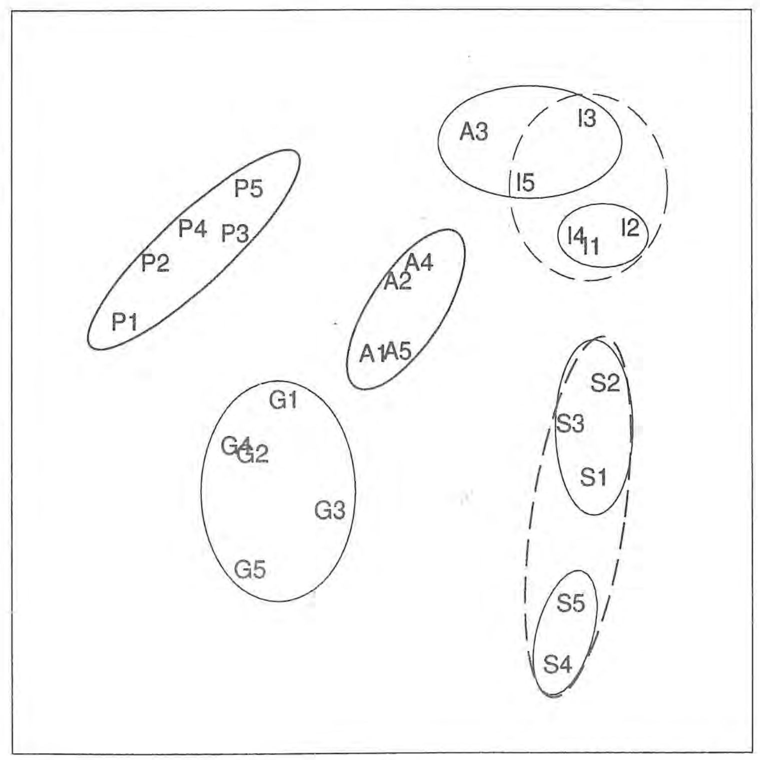


Fig. 3.5 Classification of reef crest transects (5 m) by benthic lifeform assemblages. Five replicate transects (1-5) from each of 5 sites are plotted (G: Gabuo, P:Pisang, S: Sipakal, A: Air, I: Pieh). Note the outlier A 3 in both plots. (**a**) Hierarchical clustering, (**b**) MDS ordination (Stress 0.06). Solid circles are drawn to visualise formation of groups on the 75 % similarity level. Dotted lines mark separable reef sites.

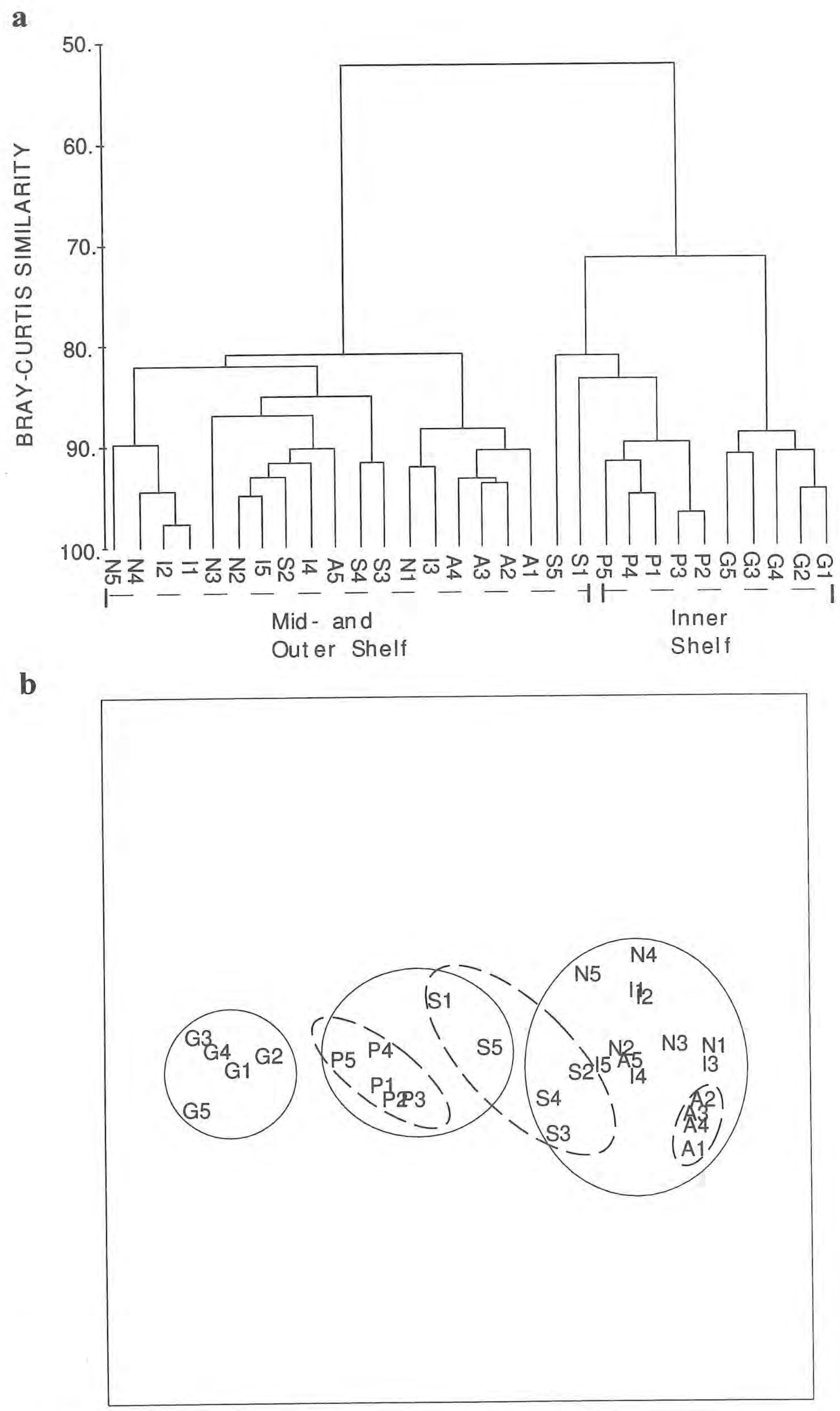


Fig. 3.6 Classification of reef slope transects (10 m) by benthic lifeform assemblages. Five replicate transects (1-5) from each of six sites are plotted (G: Gabuo, P: Pisang, S: Sipakal, A: Air, I: Pieh, N: Pandan). (**a**) Hierarchical clustering, (**b**) MDS ordination (Stress 0.05). Solid circles are drawn to visualise formation of groups on the 75 % similarity level. Dotted lines mark separable reef sites.

Reef slope

Benthic lifeform associations on shallow slopes showed a more consistent trend among reefs. The inner shelf reef sites Gabuo (I/S) and Pisang (I/S) were clearly separated from mid- and outer shelf reef sites, except two Sipakal (M) transects (S1, S5), which were grouped with the inner shelf reefs (Fig. 3.6 a). On the 75 % similarity level three clusters were differentiated: the inner shelf reef Gabuo (I/S) was split from Pisang (I/S) and the two Sipakal (M) transects and the third group consisting of mid- and outer shelf reefs. These revealed no clear pattern except for the mid-shelf reef Air (M) , which is separated by four similar transects. This pattern is in line with Figure 3.1, which already indicated close resemblance of Pieh (O/E) and Pandan (O/E) slope communities.

The MDS plot (Fig. 3.6 b) reflects these findings. In contrast to the dendrogram, four reef sites including Sipakal (M) are discernible, while transects of Pieh (O/E) and Pandan (O/E) group together.

3.1.4 MULTIVARIATE DISCRIMINATION BETWEEN SUBSTRATE ASSEMBLAGES

Apart from the distribution of benthic organisms, substrate dominance was expected to be related with the different environmental impact regimes. Since the availability and composition of primary substrate is of importance for recruitment success of benthic communities, the spatial distribution of the five main substrate categories sediment, sediment/rubble, rubble, reef rock and dead coral was analysed by multivariate classification.

Reef crest

Similarly to the classification by benthic lifeforms, two main groups were separated by hierarchical clustering: the rubble and sediment dominated inner shelf reef sites Pisang (I/S) and Gabuo (I/S) and the mid- and outer shelf reef sites Sipakal (M), Air (M) and Pieh (O/E) with higher abundance of reef rock. Five clusters were identified on the 75% similarity level. The inner shelf site transects were split in three groups, while the mid-shelf reef Sipakal (M) with one transect each of Air (M) and Pieh (O/E) was separated from the fifth group consisting of two subgroups for Air (M) and Pieh (O/E) (Fig. 3.7 a).

The MDS plot (Fig. 3.7 b) revealed the five clearly separable reef sites and underlined that the substrate assemblages at Air (M) and Pieh (O/E) were more similar than the two mid-shelf sites Air (M) and Sipakal (M), due to higher abundance of reef rock at Sipakal (M) (Fig. 3.2, Fig. 3.3).

Reef slope

Three main groups were separated on the 77% similarity level. In contrast to the reef crest classification the mid shelf reef slopes at Sipakal (M) and Air (M) group together, separable from the outer shelf sites Pieh (O/E) and Pandan (O/E) and the inner shelf reef sites Pisang (I/S) and Gabuo (I/S).

While Pisang (I/S) and Gabuo (I/S) transects were clearly separated, no site specific pattern was revealed for mid- and outer shelf reefs, indicating a similar patchiness among substrate type abundance for shallow reef slopes in mid- and outer shelf position (Fig. 3.8 a, b).

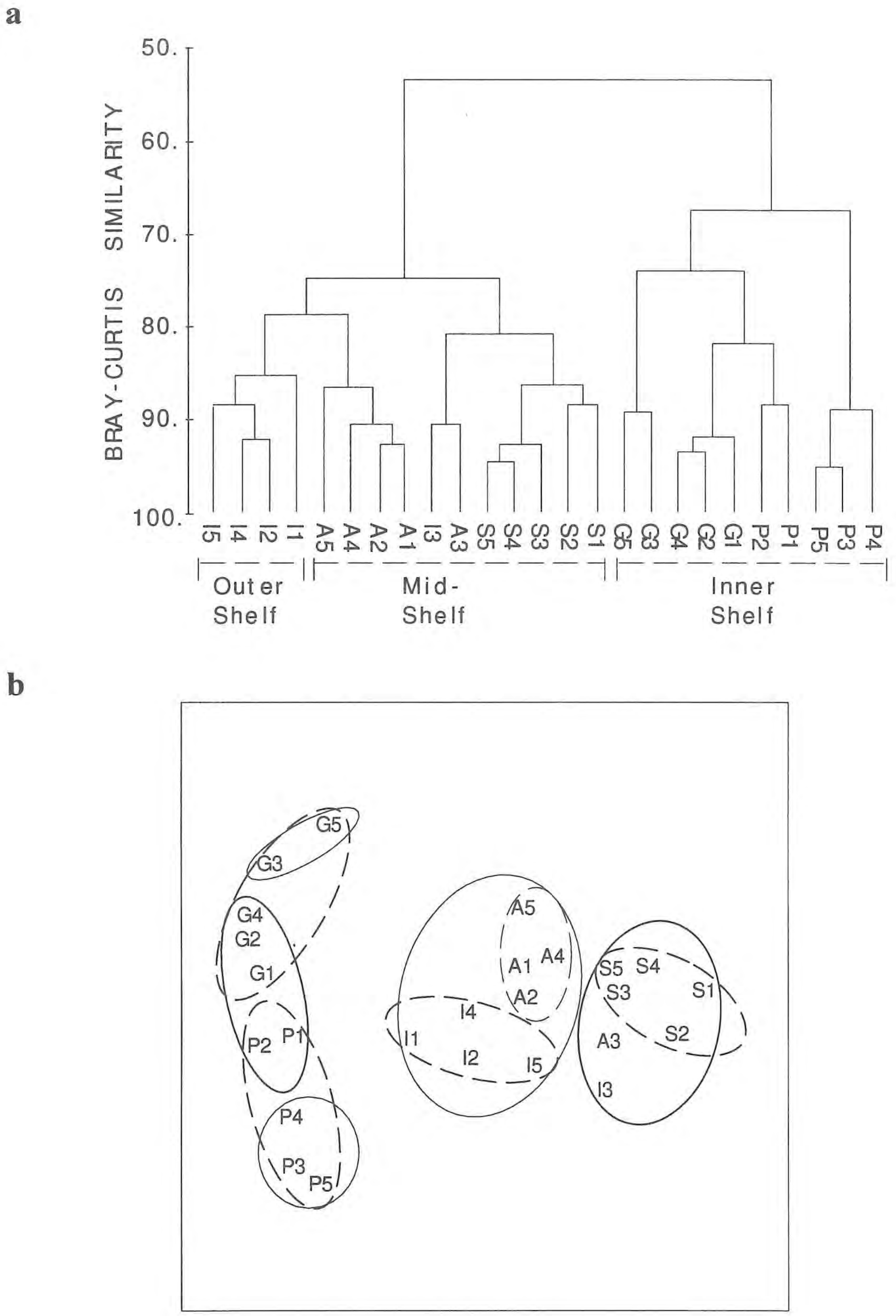


Fig. 3.7 Classification of reef crest transects (5m) by substrate assemblages. Five replicates (1-5) from each of 5 sites are plotted (G: Gabuo, P: Pisang, S: Sipakal, A: Air, I: Pieh). Note the outliers A 3 and I 3 in both plots. (**a**) Hierarchical clustering, (**b**) MDS ordination (Stress 0.06). Solid circles are drawn to visualise formation of groups on the 75 % similarity level by hierarchical clustering. Dotted lines mark separable reef sites.

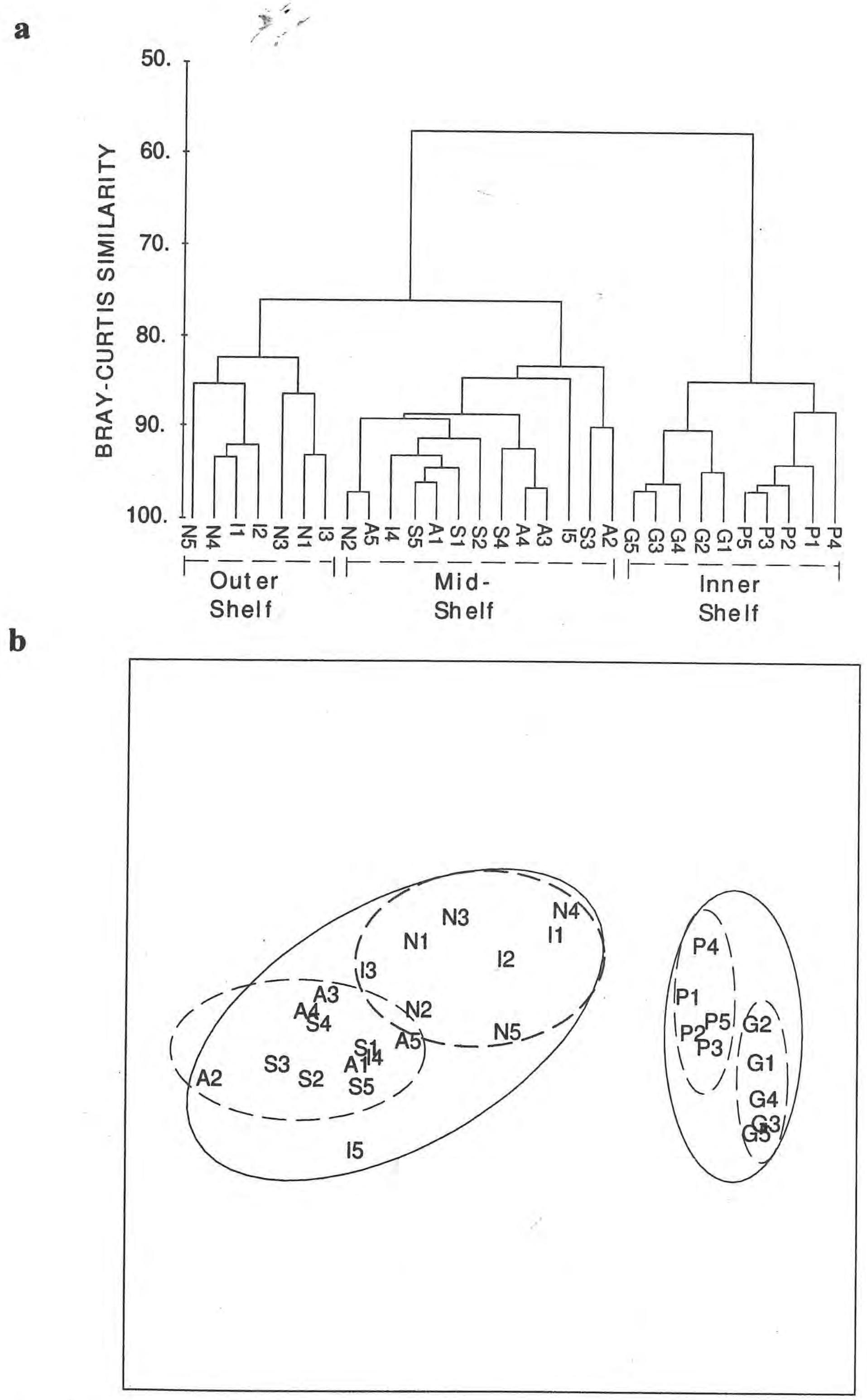


Fig. 3.8 Classification of reef slope transects (10 m) by substrate assemblages. Five replicates (1-5) from each of 5 sites are plotted (G: Gabuo, P: Pisang, S: Sipakal, A: Air, I: Pieh, N: Pandan). (**a**) Hierarchical clustering (note the outliers I4, I5 and N2 in the central cluster), (**b**) MDS ordination (Stress 0.05). Solid circles are drawn to visualise formation of groups on the 75 % similarity level. Dotted lines mark separable reef sites.

3.1.5 CORAL COMMUNITY PARAMETERS

Besides the percentage cover of live and dead scleractinian corals (Fig. 3.2; Fig. 3.3; Table 3.1), the distribution of coral growth forms was analysed. Size frequency distribution of live coral colonies as well as the relative contribution of corals in growth position, displaced colonies and live coral fragments to the total number of live corals were measured and compared. Occurrence of lesions in the coral tissue was sampled, since it was expected to be a further potential indicator for existing degrading impacts. Investigations on coral recruitment potential were carried out at two selected sites, the inner shelf reef site Pisang (I/S) and the outer shelf reef site Pieh (O/E).

Table 3.1 Mean live and dead coral cover [%] for reef crest and slope habitats at all surveyed reef sites.

	Reef crest		Reef slope	
Site	Live coral cover	Dead coral cover	Live coral cover	Dead coral cover
Gabuo (I/S)	7	3	0	0
Pisang (I/S)	25	6	14	1
Sipakal (M)	25	2	23	3
Air (M)	31	7	27	2
Pieh (O/E)	47	3	25	3
Pandan (O/E)	-	-	22	1

Coral growth form distribution

Seven of eleven reef crest and slope stations had relatively similar live coral cover between 22 and 31% (Table 3.1). In contrast, the relative abundance of growth forms indicated distinctive differences among coral communities in both habitats and among reef sites (Fig. 3.9). Dominance of one particular growthform was rare (foliaceous corals on the reef crest at Pisang (I/S) and branching Acropora in the reef crest transects at Gabuo (I/S)), while dominance of two to three growth forms was common on mid- and outer shelf reef sites.

As expected, strongest differences between habitats in different depths were found at turbid inner shelf reef sites, while highest similarity between both habitats was found at the outer shelf reef Pieh (O/E) (Fig. 3.9). The number of abundant growthforms increased from inner shelf reef sites to outer shelf reef sites (Table 3.2). Ranking of growthforms according to their respective dominance at each habitat and reef site revealed a complex pattern (Table 3.2). Foliaceous corals were abundant in crest and slope habitats on inner shelf and outer shelf reef sites, but were ranking low on mid shelf reef sites. In contrast, tabulate *Acropora* colonies where most abundant on mid shelf reef crests, but were relatively uncommon on crest and slope habitats of inner and outer shelf reef sites. While certain growthforms, such as submassive corals, branching corals and corymbose and digitate *Acropora* colonies occurred widely but ranked consistently low, encrusting coral colonies were common and abundant community members in both habitats at most reef sites (Fig. 3.9).

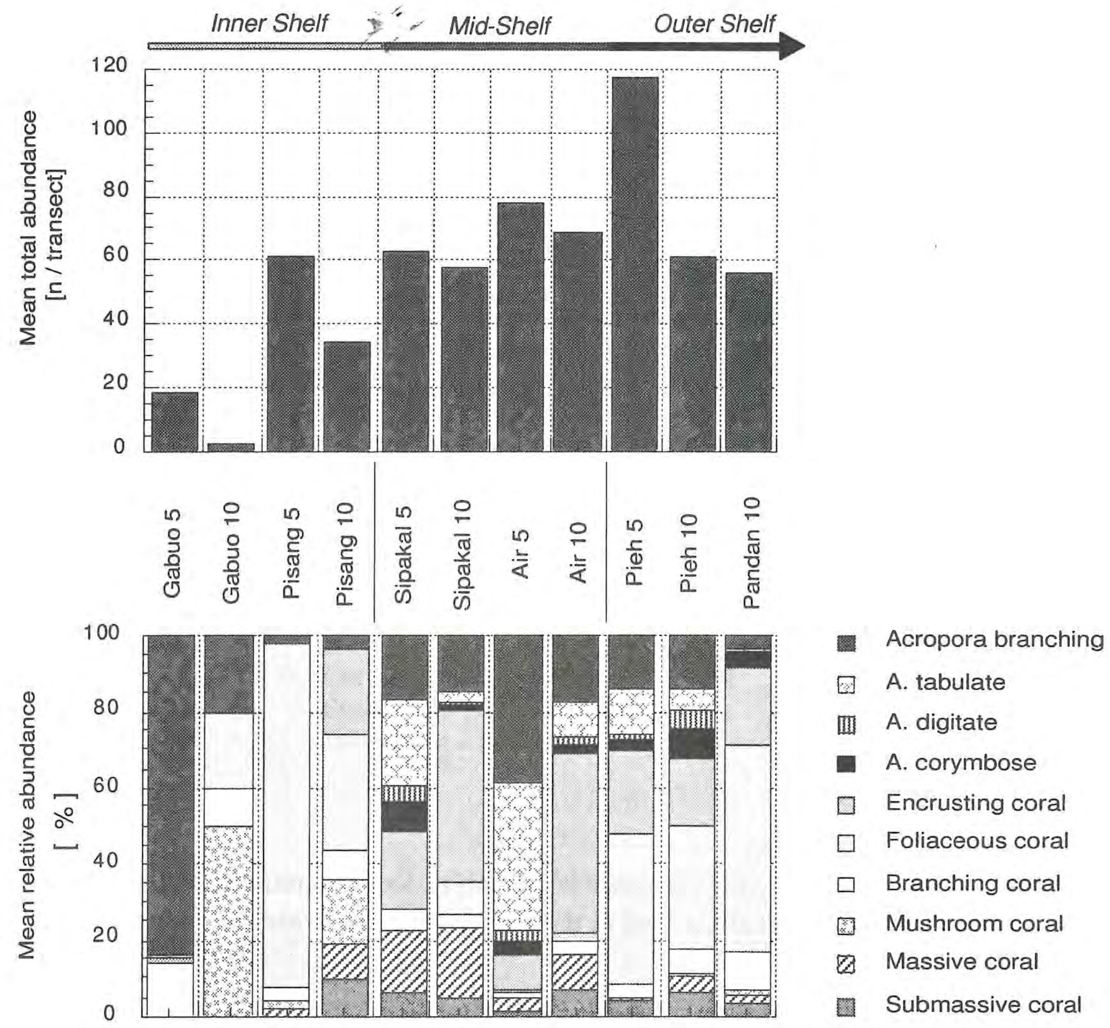


Fig. 3.9 Mean relative and mean total abundance of coral growthforms.

The presence of four distinctively different growthform assemblages at five reef crest sites underlines the high variability of coral communities among reef sites. Based on the mean relative abundance of dominant growthforms, four community types were distinguished in the reef crest habitat (C):

C 1. ACB - type:

More than 80% branching *Acropora* (Gabuo (I/S)).

C 2. ACT / ACB - type:

Tabulate and branching *Acropora* dominate with 20-40% each, with encrusting corals being the third dominant growthform (Sipakal (M), Air (M)).

C 3. CF - type:

More than 80% foliaceous corals (Pisang (I/S))

C 4. CF / CE - type:

30-50% foliaceous corals with about 20% encrusting corals (Pieh (O/E)).

Table 3.2 Presence- absence matrix of coral growth forms for all surveyed reef sites and habitats. Numbers indicate ranks based on mean relative abundance of growthforms, ranging from 1 for highest abundance to 10 for lowest abundance (ACB: *Acropora* branching, ACT: *Acropora* tabulate, ACD: *Acropora* digitate, ACO: *Acropora* corymbose, CE: encrusting coral, CF: foliaceous coral, CB: branching coral, CMR: mushroom coral, CM: massive coral, CS: submassive coral, GF Total: total abundant growth forms).

	Reef crest					Reef slope					
	Gabuo	Pisang	Sipakal	Air	Pieh	Gabuo	Pisang	Sipakal	Air	Pieh	Pandan
ACB	1	4	3	2	3	2	7	3	2	3	5
ACT	3	-	1	1	4	-	-	7	4	7	7
ACD	-	-	8	6	9	-	-	9	7	7	-
ACO	-	-	5	5	7	-	-	8	8	4	4
CE	3	6	2	3	2	-	2	1	1	2	2
CF	-	1	-	9	1	2	1	4	9	1	1
CB	2	2	7	7	5	3	6	6	6	5	3
CMR	-	3	-	-	-	1	3	-	-	9	8
CM	-	5	4	4	8	-	5	2	3	8	6
CS	-	-	6	8	6	-	4	5	5	6	5
GF_{Total}	4	6	8	9	9	4	7	9	9	10	9

These differences among coral growthform assemblages were less pronounced on reef slopes (S). Two community types were distinguished at the six surveyed reef sites :

S 1. CE / ACB / CM - type:

Encrusting corals account for about 50%, followed by branching Acropora and massive corals with about 10-20% (Sipakal (M), Air (M))

S 2. CF / CE - type:

30-50% foliaceous and about 20% encrusting coral colonies dominate communities (Pisang (I/S), Pieh (O/E), Pandan (O/E)).

In the case of the Gabuo (I/S) reef slope no assemblage was distinguished. The slope was dominated by rubble interspersed with sediment or sediment/rubble patches. Only ten live corals were found in total on all Gabuo (I/S) slope transects, consisting of five mushroom corals and fragments of branching *Acropora* and foliaceous corals. Type S 2 was similar to C 4, since reef crest and slope transects at Pieh (O/E) showed comparable growthform assemblages (Fig. 3.9).

The ranking of less dominant growthforms was found to be highly variable between habitats of the same type (Table 3.2) and caused complex coral community patterns. It was of interest, how strong these less dominant categories were corroborating or refuting the distinguished assemblage types. In order to test the a priori distinction between the mentioned growthform assemblages, a multivariate classification of the surveyed reef sites and habitats was carried out based on the mean relative abundance of growthforms at each site. According to the progressive downweighting of common categories or species through no transformation, square root transformation and 4th root or logarithmic transformation (Clarke & Warwick 1994), data of the Bray-Curtis similarity matrix were root transformed. Thereby a moderate transformation retained the quantitative information and downweighted the category dominants.

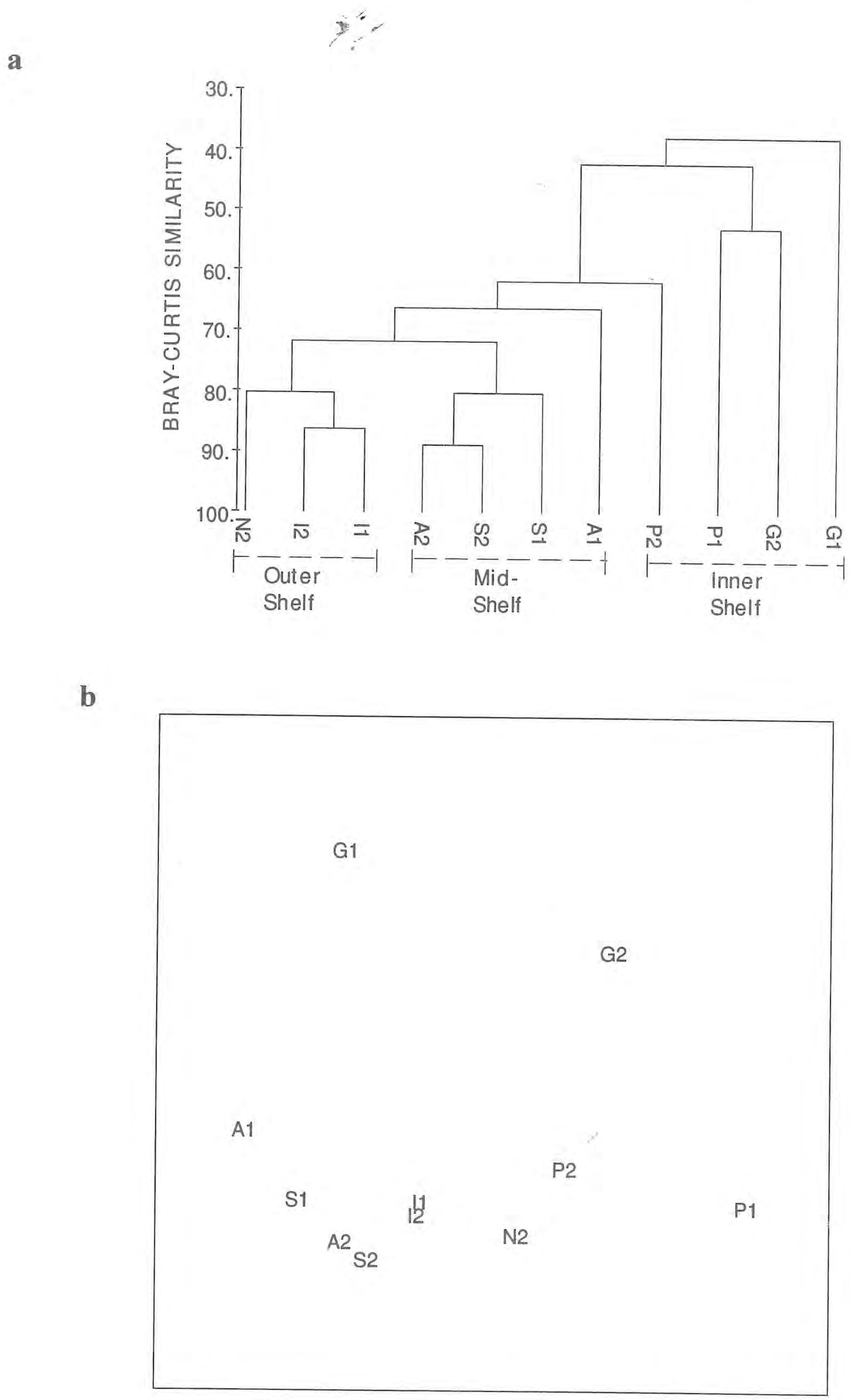


Fig. 3.10 Classification of reef sites and habitats by coral growthform assemblages. **(a)** Hierarchical clustering, **(b)** MDS ordination (Stress 0.06). Reef crest (1) and reef slope (2) are plotted for 6 reef sites (G: Gabuo, P: Pisang, S: Sipakal, A: Air, I: Pieh, N: Pandan). Reef crest data for Pandan (N1) are not displayed.

The dendrogram and MDS ordination (Fig. 3.10 a, b) revealed mainly coincidence between the a priori separation of assemblage types and the statistical classification. The similarity of assemblage type C4 and S2 was reflected, since Pieh (O/E) crest and slope transects (I1, I2 in Fig. 3.10 a, b) showed a higher similarity than among slope transects at Pandan (O/E) and Pieh (O/E). In contrast, a separate classification in the dendrogram seemed to refute the inclusion of the Pisang (I/S) slope in type S2. The MDS plot indicated that the closest similarity with the Pisang (I/S) slope existed with the Pandan (O/E) slope assemblage, which would again be in line with the inclusion in type S2.

Slope transects of Air (M) and Sipakal (M) were closely grouped together, corresponding to type S 1. Crest transects of Air (M) and Sipakal (M) were less similar than expected, possibly due to the relative differences in abundance of branching and tabulate *Acropora* (Fig. 3.4).

MDS plot and dendrogram both underlined the dissimilarity between the inner shelf transect sites. The branching-*Acropora* dominated reef crest at Gabuo (I/S) (type C1) was distinctively different from the foliaceous coral dominated crest habitat at Pisang (I/S) (type C3) and the two inner shelf slope assemblages.

Size - frequency relationships

The size class distribution for living coral colonies (Fig. 3.11) of the surveyed reef sites was mostly characterised by a rapidly decreasing number of colonies with increasing size. The reef crest transects at Pieh (O/E) showed exceptionally high abundance of corals in the two smallest size classes (note the different x-axis in Fig. 3.11), with nearly twice as much colonies per size class compared to reef crest transects at Air (M) and Sipakal (M). Reef crests at Sipakal (M), Air (M) and Pieh (O/E) had a comparatively high abundance of colonies in the size classes 50 - 100 cm and 100 - 200 cm, while corals of this size were hardly present in reef slope transects of all reef sites. Comparing the abundance in the three size classes with the largest diameter, Air (M) reef crest transects dominate with the highest number of large coral colonies (n = 77) in all 5 transects, followed by Pieh (O/E) (n = 43) and Sipakal (M) (n = 31). Accordingly, mean live coral colony size was highest on Air (M) reef crests with 36 cm (Table 4.1.3), followed by reef crest habitats at Pieh (O/E) and Sipakal (M) and the reef slope at Air (M) with 20 cm. While mean maximum live coral diameter varied only between 14 and 20 cm on reef slopes, mean size on reef crests ranged from 16 to 36 cm.

Table 3.3 Mean maximum live (LC) and dead (DC) coral colony size [cm] for reef crest and slope habitats at all surveyed reef sites. Asterisks indicate missing values for Pandan reef site.

	Reef crest		Reef slope	
Site	Mean max. LC diam.	Mean max. DC diam.	Mean max. LC diam.	Mean max. DC diam.
Gabuo (I/S)	23	23	15	-
Pisang (I/S)	16	22	17	15
Sipakal (M)	20	45	18	28
Air (M)	36	46	20	28
Pieh (O/E)	20	32	14	15
Pandan (O/E)	*	*	14	43

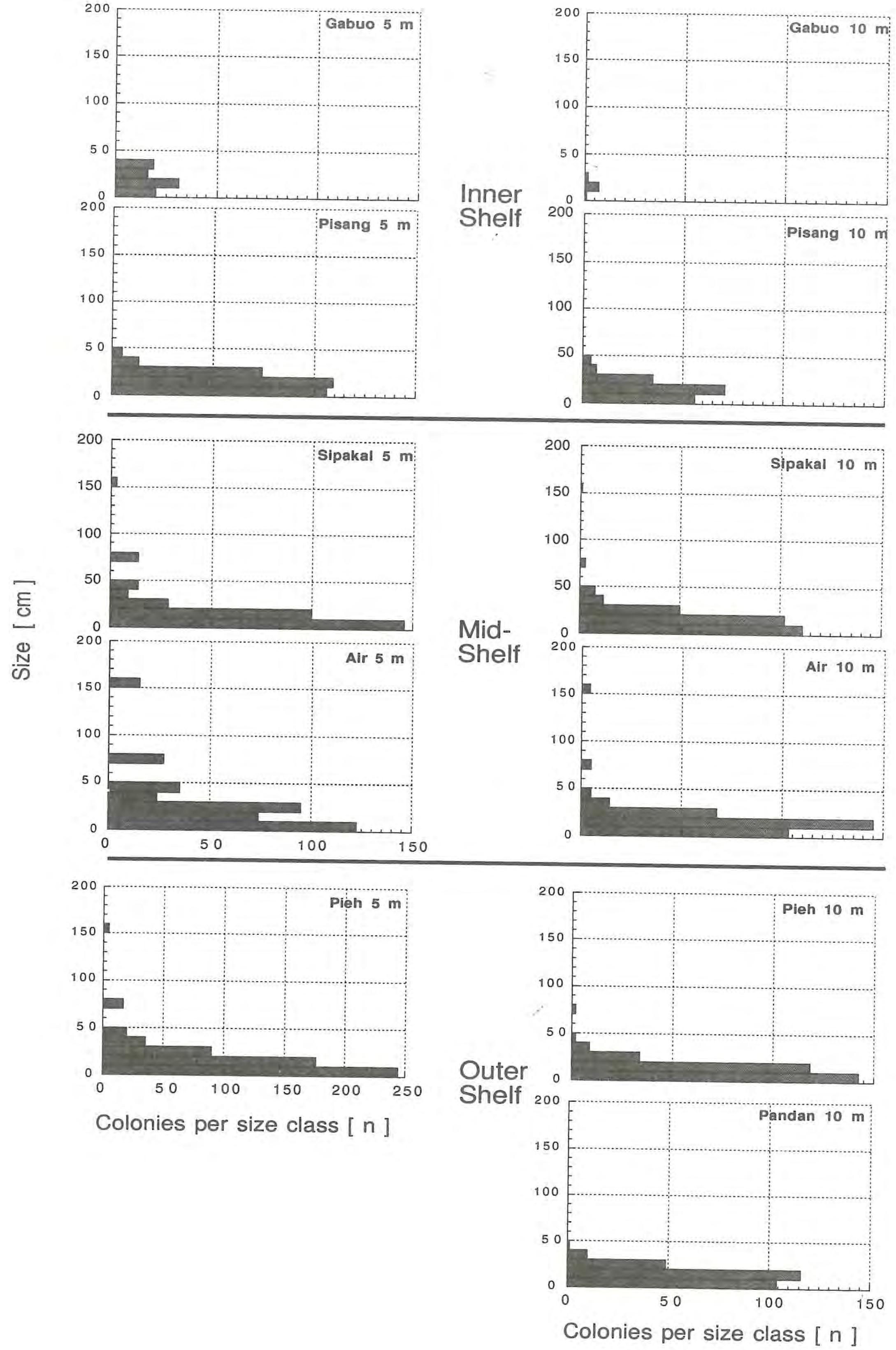


Fig. 3.11 Coral size class distribution. Pooled transect data for each habitat and site. Size class (Sc) 1: 0-10 cm, Sc 2: 10-20 cm, Sc 3: 20-30 cm, Sc 4: 30-40 cm, Sc 5: 40-50 cm, Sc 6: 50-100 cm, Sc 7: 100-200 cm. Note the different X-axis for "Pieh 5 m".