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Thematic mapping of reefs by processing of simulated SPOT satellite data: application to the *Trochus niloticus* biotope on Tetembia Reef (New Caledonia)

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ABSTRACT: Exploitation of trochus *Trochus niloticus* is important for Pacific islanders. The shell yields valuable mother-of-pearl of which 2000 tons were exported from New Caledonia in 1978. Knowledge of the exploitable stock requires a good estimate of the surface area occupied by this gastropod which colonises dead coral reefs. Because trochus environments in New Caledonia are very extensive and access is difficult, synoptic methods of estimation are called for. High resolution remote sensing appears to be a particularly suitable method. Simulation of images to be obtained from the French SPOT satellite was carried out in New Caledonia in December 1983. This paper deals with the method used to process the digital high resolution images that will be produced by SPOT. Results are presented as thematic maps of the main reef environment types, with their respective surface areas. Among hard reef bottom covers, the trochus environment was finely analysed and areas identified were compared with ground truth observations and with aerial photograph interpretation. The potential usefulness of high resolution SPOT images is confirmed for thematic mapping and evaluation of shallow-living reef resources.

INTRODUCTION

The main island of New Caledonia is separated from the ocean by a succession of barrier reefs which enclose a large lagoon more than 1500 km long and up to 40 km wide. Like most Pacific islanders, residents of New Caledonia exploit the living resources of the reefs and lagoon, but are also endeavouring to gain a better understanding of them.

The lagoonal reef formations comprise a wide variety of biotopes which are generally permanently colonised by animal and plant species. To assess a given biological resource, it is essential to estimate its habitat area. Such areal assessments require a method capable of identifying, on bionomic maps of reef environments, the type of environment that, potentially, comprises nearly all the individuals of the population concerned. Ground sampling, by quadrats or transects, yields information on the density of stock, which, multiplied by the total area of the biotope considered, will lead to an accurate assessment of the biomass of the exploitable fraction of the stock.

Conventional methods of bionomic mapping rely on examination of aerial photographs, nautical charts and underwater observations, carried out according to a sampling plan suited to the environment type under study. While these methods are usually satisfactory for areas of a few hectares, they are inadequate for environments extending over several dozen square kilometres. In the latter case, either the ground sampling plan becomes gigantic and entails all sorts of technical and financial difficulties, or else interpolation and extrapolation of the results give rise to significant errors in the area estimation (hence of biomass). Assessment of the trochus resource of New Caledonia came up against these problems associated with very extensive areas.

Trochus niloticus has been exploited and exported from New Caledonia since the beginning of the century for its nacreous shell which is used in the man-

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ufacture of mother-of-pearl products. Trochus constitutes an important source of income for the coastal communities of New Caledonia, who jealously guard the trochus colonies established on the reefs in front of the village, referring to them as their treasure-chest.

Production was very irregular before World War II; it practically ceased during the war years, then soared for a time until it became less attractive because of highly lucrative employment available on the nickel mines. A slump in the mining industry however brought about a revival of interest in the traditional trochus fishing activity. The New Caledonian stock, which had been left unfished for nearly 10 yr, allowed a record export figure to be reached in 1978, when 2000 tons of shells were shipped to Europe and Asia. New Caledonia supplied one third of the total world production in that year (Bour et al. 1982).

Trochus live in shallow water on reef flats consisting of dead coral slabs with many crevices and scattered coarse rubble. This bottom type can be found on most of the reef formations in the lagoon (fringing reef, inner lagoon reef, and barrier reef). Thus the environment inhabited by trochus stocks represents a large fraction of the 20000 km^2 of the New Caledonian lagoon. Thematic mapping of land and coastal areas by satellite image processing has been successfully carried out for a number of years. It therefore seemed worthwhile to try to apply this technique to shallow reef areas.

METHODS

SPOT satellite and radiometric simulation. SPOT (Satellite Pour l'Observation de la Terre), a second-generation earth observation satellite with a sun-synchronous orbit, was launched by France in February 1986. It passes vertically over New Caledonia every 26 d at 1015 h local solar time. Its payload consists of 2 HRV (High Resolution Visible) sensors, technical specifications for which are given in Table 1 (CNES 1983).

SPOT will be very useful for observation of coastal environments characterised by a high degree of spatio-temporal variability (Loubersac 1983); it can produce high resolution images and has the ability to acquire data repetitively for the same scene (total image of 60×60 km^2) by off-nadir viewing. The technique of tilting the instrument sideways provides a quick revisit capability on specific sites, for example at the equator the same area can be targeted 7 times during the 26 d of an orbiting cycle.

Simulated SPOT imagery, recorded before the launching of the satellite, was achieved by radiometric methods (Lannelongue & Saint 1981) using an airborne 'Deadalus' radiometer. These data were restructured to give a radiometry equivalent to that of the HRV channels.

Table 1. Technical specifications of the HRV sensor

	Multiband mode XS	Panchromatic mode XP
Spectral channels (μm)	XS1 0.50–0.59 XS2 0.61–0.69 XS3 0.79–0.89	0.51–0.73
Resolution (m)	20×20	10×10
No. of pixels[1]/line	3000	6000
Length of 1 line (km)	60	60

Pixel = picture element : point of the remote sensed image representing 20×20 m of the ground with XS mode and 10×10 m with XP mode

In December 1983, the GDTA[1] coordinated a SPOT simulation campaign focussed on New Caledonia. For the coastal area, the 4 main objectives were: bathymetric studies (SHOM[2]); mapping of intertidal zones with a view to inventorying aquaculture sites (IFREMER[3]); geological studies (BRGM[4]); and observation of reef environments, the general theme with which this paper deals (ORSTOM[5] and IFREMER).

The simulation campaign was carried out on 31 flight transects over both land and lagoon environments. On 17 December, Transect 22 was scanned at 0936 h (low tide, coefficient 0.6) over Tetembia reef which is part of the large outer reef located on the west coast, north of Uitoe Pass (Fig. 1).

Data processing. The data are composed of 4 files. Each file contains the values of the pixels on the channel concerned. The spectral response of the observed areas is different in each of the basic channels: XS1, XS2, XS3 or XP. These responses are used to discriminate the different reef types and thus, to map them. The panchromatic channel (XP) with 10 m resolution provides morphological details.

The XS1 (green) and XS2 (red) channels penetrate the water to various depths; they are used together to differentiate underwater features at depths 0 to 5 m. At greater depths, only XS1 allows bottom types to be discriminated.

On account of the relatively high correlation of the

[1] GDTA: Groupement pour le Développement de la Télédétection Aérospatiale
[2] SHOM: Service Hydrographique et Océanographique de la Marine
[3] IFREMER: Institut Français de Recherche pour l'Exploration de la Mer
[4] BRGM: Bureau des Recherches Géologiques et Minières
[5] ORSTOM: Institut Français de Recherche Scientifique pour le Développement en Coopération

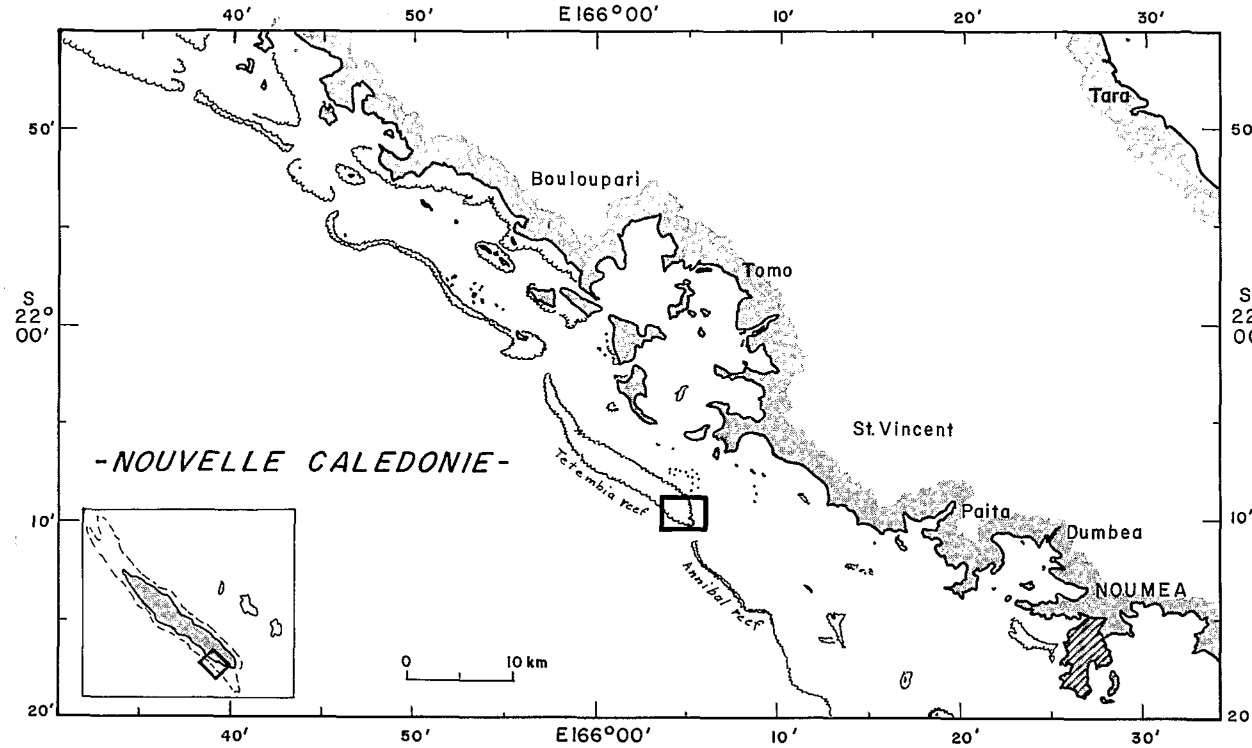

Fig. 1. Location map

XS1 and XS2 channels (r = 0.6, 250000 pixels), analysis by principal components results in the main Axis 1 accounting for 90 % of the total variance which is not good for thematic classification. But the boomerang structure of the bidimensional histogram, constructed from XS1 and XS2 channels (Fig. 2), shows that it is more useful to represent the histogram with polar coordinates; this allows better distribution of the data than representation with orthogonal coordinates (XS1, XS2).

Polar coordinates (i.e. for each pixel, distance from the origin and angle with the first axis XS1 in the bidimensional histogram, instead of orthogonal coordinates in that histogram) produce a scattering of the pixels more suitable for classification, because (1) the distance to the origin is directly linked to depth, as light absorption varies with the depth of water penetrated; (2) the polar angle allows 2 main types of environments to be differentiated: hard bottom covers (brown-coloured, near the red channel XS2) and soft bottom covers (blue-green, near the green channel XS1).

Two pseudo-channels are therefore calculated by combining the original images (image with XS1 values and image with XS2 values of the pixels). Thus, for each pixel having XS1 and XS2 as orthogonal coordinates on the bidimensional histogram, its polar coordinates are:

$$\text{Distance} = \sqrt{(XS1)^2 + (XS2)^2}$$

$$\text{Angle} = \text{Arctan}\,(XS2/XS1)$$

The correlation between the 2 images related to the pseudo-channels is only r = 0.2 for 250000 pixels. Analysis by principal components gives 60 % of the total variance on the main Axis 1 and 40 % on Axis 2.

Because of the decorrelation achieved, it is possible, by simple thresholding of the values on the 2 pseudo-channels, to define 5 classes of pixels and to calculate the surface area of these classes (Fig. 3). The pixels of the class identified as reef flat (i.e. the shallow reef zone, depth range 0 to 2 m) are then isolated, analysed by principal components and classified. Five new classes are identified and the respective areas calculated (Fig. 4).

RESULTS

First classification: general themes

A first map (Fig. 3) was obtained by processing the bidimensional histograms, without any prior detailed information about Tetembia reef. It can therefore be regarded as having been drawn up objectively.

Ground verification of the map led to the following

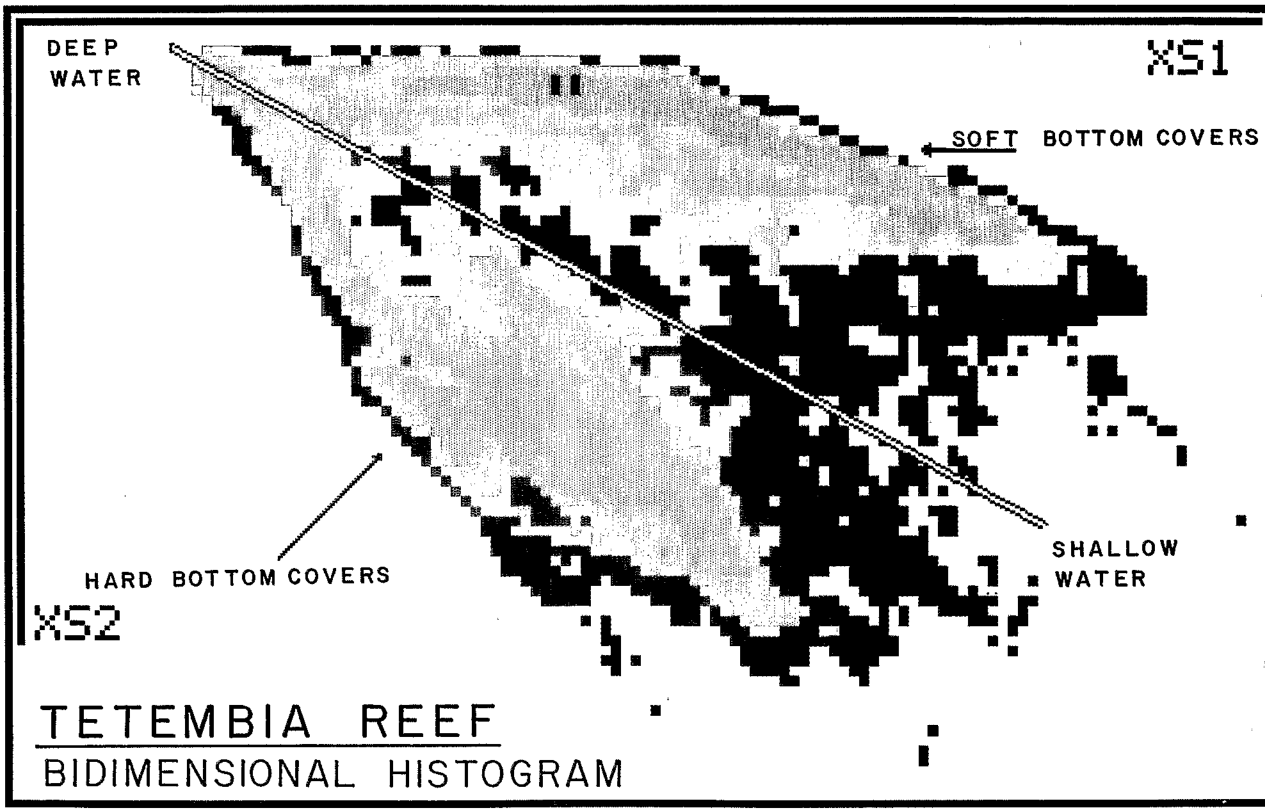

Fig. 2. Tetembia reef: XS1/XS2 bidimensional histogram

conclusions: processing separated correctly the soft bottom and hard bottom themes; hard bottom covers in shallow water (Theme 1) have the same structure on the outer reef flat as on the inner reticulate reef flat, with massive slabs covered with rubble and displaying scattered patches of branching corals (*Acropora* spp.) which are denser towards the rim; living corals were also correctly identified (Themes 2 and 3). They constitute the upper part of the spur-and-groove zone of the outer reef slope and also the base of the reticulate reef flat. Examination of a black-and-white aerial photograph from the French National Geographic Institute (IGN) shows this southern portion of Tetembia reef to be a large corridor through which tidal waters circulate. The water flow has worn away the tip of the reticulate reef flat, where only a few coral heads remain. The considerable water movement in this area understandably promotes the development of living corals at the tip of the reticulate reef flat and around the remaining coral heads; soft bottom covers were separated into 2 themes (4 and 5). Examination of the IGN aerial photograph reveals the effect of depth on this division. The 2 bottom types have the same covers, that is, white sand with scattered patches of branching corals. Water movement has carved out a hollow in the sediment between the 2 largest coral heads. This small hollow was correctly identified by the method used.

Second classification: hard bottom themes

The general theme hard bottom covers was subdivided into 5 bionomic themes (Fig. 4) which, when compared with ground verification, lead to the following comments: the outer rim of the barrier reef (Theme 1) corresponds to a reef flat consisting of branching corals of small size but high density which are only slightly under water at low tide and thus give a high response in the red channel (XS2); the living corals are also represented by Themes 3 and 5. The former corresponds to the living parts on the rim of the reticulate reef, while the latter clearly identifies the inner barrier reef flat consisting of scattered patches of branching corals. These 2 zones do not appear to be differentiated by depth but rather by the density of the living corals; the reef flat (Themes 2 and 4) has the usual structure of more or less creviced slabs covered with coarse rubble of dead branching corals. Theme 2 corresponds to the shallower portion of the flat; its strong reflectance is further increased by the presence

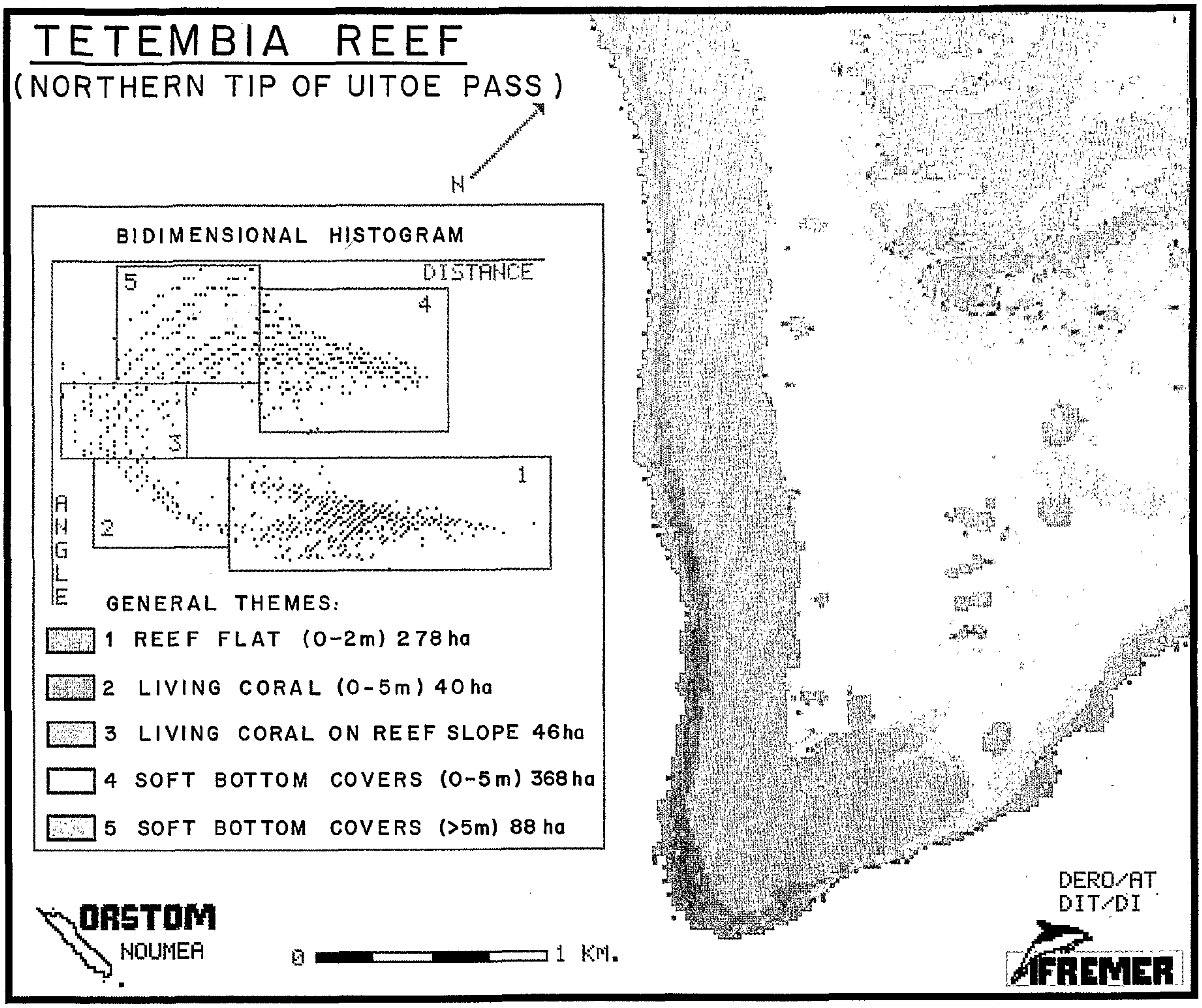

Fig. 3. Tetembia reef: general themes

of fine rubble and white sand. Theme 4 is the type of bottom suitable for trochus.

Estimation of surface areas

Computer processing of the first classification gives the number of pixels forming each theme. Knowing the ground area of 1 pixel, it is easy to work out the surface area covered by each theme. The radiometric results were compared with the areas measured by planimetry on the aerial photograph, the scale of which is known. The deviation was found to be respectively 16 % for the hard reef flat (Theme 1) and 15 % for the soft bottom covers (Themes 4 and 5). In both cases, the simulated SPOT image gives a larger surface area; it is hard to say which method is closer to the truth since (1) the SPOT image is not corrected geometrically; (2) the limits of the theme are difficult to project on the photograph (the processed image is synthetic); (3) the many details on the aerial photograph make it impos-

Table 2. Comparison of areas calculated by planimetry and by data processing

Theme	Areas (ha)	
	Aerial photograph (planimetry)	Simulated SPOT image (radiometry)
1	26	33
2	16	30
3	5	26
4	124	130
5	43	54

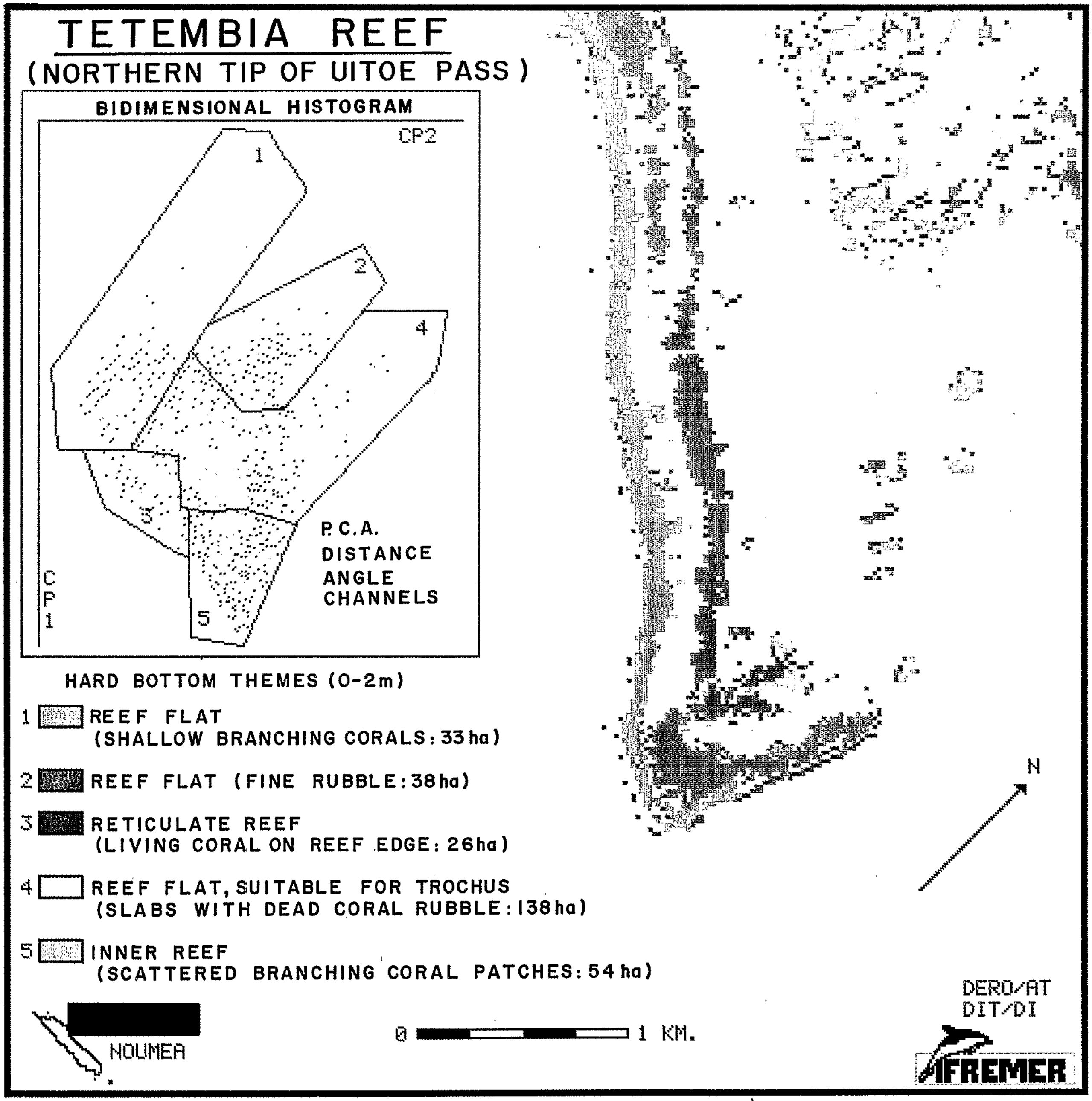

Fig. 4. Tetembia reef: hard bottom themes

sible to delimit the hard reef precisely (the photograph gives a true picture that is complex and diversified); (4) planimetric calculations are inaccurate for small areas measured on the photograph.

For the second classification (hard bottom covers), the areas estimated from remote sensed data and from the aerial photograph are given in Table 2.

Despite the discrepancy between the estimations of small areas, homogeneity of the 2 methods can be accepted by Chi-square test (4.87, P = 0.3). The high spatial resolution of the SPOT system is probably affecting the area calculation for smaller scattered patchy areas (Themes 2 and 3) the size of which is similar to that of SPOT's pixel. Planimetry is also not very accurate for such areas, as noticed above.

CONCLUSIONS

This first attempt at mapping shallow reef zones by processing simulated SPOT image data proves promising since (1) the biotope sought (bottom cover suitable for trochus) was correctly identified; (2) processing achieved good discrimination of the different environments by moderately smoothing out faunistic features, thus demonstrating the value of the high resolution satellite data that SPOT makes available; (3) the surface areas of the different biotopes were estimated with a degree of precision sufficient for our purposes; (4) reef areas, under a few metres of water, have the advantage over land areas of a lower correlation between the XS1 and XS2 channels, due to the water layer which acts as a filter for the red channel (XS2); the living corals furthermore give a high spectral response in this channel. These facts, among others, account for the good results achieved with only 2 channels.

SPOT's high resolution will, in the very near future, enable the bionomic features of reef environments to be rapidly and objectively interpreted and, through repetitivity of scenes, facilitate monitoring of changes in time.

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