The Structural and Thematic Mapping of Coral Reefs Using High Resolution SPOT Data: Application to the Tétembia Reef (New Caledonia)

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Abstract

This paper describes the application of high-resolution SPOT data for the structural and thematic mapping of shallow coral reefs. Results are presented as structural and thematic maps of the main reef environment types. Different substrate themes including soft bottom, coral débris, coral rubble, and living coral have been identified. The separation of various living coral themes, as measured by differences in areal coral density, has also been achieved.

Introduction

One of the basic aims in coral reef research is to gain a better understanding of the spatial and temporal distributions and abundance of the reef cover types. Conventional methods of mapping reef cover types typically rely on the examination of aerial photographs, nautical charts and underwater observations, undertaken according to a sampling methodology dependent on the reef cover type under examination. While such techniques are usually satisfactory for areas consisting of a few hectares, they are inadequate for reef environments extending over many square kilometers, as in the case of barrier reefs. Such ground sampling techniques tend to be irregular in space and time, and the extrapolation of these techniques to such large areas can give rise to significant errors in the estimation of reef types, as well as entailing all sorts of technical and financial costs.

The principal advantage of satellite remote sensing is that it can collect certain coral reef information more uniformly in both time and space. SPOT (Satellite Pour l'Observation de la Terre) is very useful for the observation of the coral reef environment, as it is characterised by a high degree of spatio-temporal variability. It has the resolution close to that of traditional aerial photography and has the ability to acquire data repetitively for the same scene by off-nadir viewing. Coral reef applications in which remote sensing data have been utilised or are planned include:

- Coral reef cartography for the accurate identification and evaluation of the spatial distribution of reefs. Such information is often required for the purposes of coral reef resource management (Kenchington and van Claasen, 1988).
- Topographical and structural aspects of coral reefs, which are used in geophysical surveys, studies in reef morphology and stratigraphy (LeMaire *et al.*, 1987).
- Qualitative and quantitative evaluation of vegetation cover (Belsher, 1987; Ben Moussa *et al.*, 1989).
- Natural catastrophy (e.g. cyclone) damage analysis (LeMaire *et al.*, 1987).
- Evaluation of zones for aquaculture development (Loubersac *et al.*, 1987).
- Studies of coral calcification and accretion studies (Kuchler *et al.*, 1986).

- The dynamics of coral spawn dispersal and settlement for the study of the coral reef reproduction cycle (Kuchler *et al.*, 1986).

Much of the research work in the area of coral reef remote sensing covers the bathymetric aspects of the reefs (Fourgassie and Le Guic, 1987; Jupp 1988) and the thematic mapping of the coral reef substrate (Jupp *et al.*, 1985; LeMaire *et al.*, 1987). Certain methodologies have been commercialised, such as the MPA microBRAIN system (MPA, 1988; Harrison *et al.*, 1989). With particular reference to thematic mapping in New Caledonia, Bour (Bour *et al.*, 1986) have produced thematic maps of the Tétembia reef using radiometric data combined with aerial photography and, in French Polynesia, Belsher (Belsher, 1987) has performed a classification of the major themes of the Tahiti-Mooréa coral ecosystem. It is the purpose of this paper to map the coral reef substrate themes using high-resolution SPOT data. The data used in this study cover the Tétembia Reef in New Caledonia.

Remote Sensing of Coral Reef Environment Using SPOT

Numerous theoretical studies have been undertaken to obtain a model for extracting bathymetry and substrate information from passive multispectral remotely-sensed data (Lyzenga, 1978; Lyzenga, 1981; Jupp, 1988). At a given wavelength, the radiation recorded at the sensor may be resolved into components involving the atmosphere and radiation emerging from the water column. This latter component includes effects due to what is in the water, substrate and the depth of water. It seems that, at first sight, it would be difficult to retrieve useful parameters from the spectral data without some sort of auxilliary information. However, simple algorithms have been implemented in an attempt to map the bathymetry, assess water turbidity, and map the type of substrate. Algorithms which have been used successfully in the mapping of the coral reef substrate include band-ratioing (Jupp, *et al.*, 1985; Jupp, 1988) and the creation of pseudo-bands from the original spectral bands (Bour *et al.*, 1986; Belsher, 1987). Some of these algorithms have led to maps of the granulometric and mud indices for coral atolls to be produced (LeMaire *et al.*, 1987). However, the existence of water turbidity, the effects of the atmosphere on the radiation emerging from the water column, and the mixing of different reef substrates within a given pixel will often limit the effectiveness of many such algorithms.

Of the three SPOT spectral bands (XS1, XS2 and XS3), only the first two bands are used, as the depth of penetration of the infrared XS3 band in the water mass is very much reduced. The XS1 band (0.50-0.59 μm) has the greatest depth of penetration (up to 15m) whereas the XS2 band (0.61-0.68 μm) penetrates to a maximum depth of approximately 5m. The XS1 band is more sensitive to variations in the substrate and band XS2 most sensitive to variations in depth.

Materials and Methods

Area of Investigation: 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. The area investigated is located in the region North of the Uitoe Passage of the Tétembia Reef at approximately 22°10'S and 166°05'E (Figure 1).

The area of investigation comprises an outer reef enclosing a submerged lagoon pattern reef, separated by mean distance of about 1 km. The lagoon reef is thought to be an older reef, having been formed prior to the existing outer reef, and is characterised by being highly dendritic. The lagoonal bottom is sandy in nature and has a depth varying between 2m to approximately 10m. Various near-surface rising coral patches are scattered throughout the lagoon.

Imagery: A SPOT image of the Baie de Saint Vincent and Tétembia reef was acquired by CNES in August 1986. The level of pre-processing (level 2) included geometric corrections as well as radiometric corrections. The image was analysed using Latical/ORSTOM software.

Ground Truth: During the establishment of ground truth, underwater observations of the reef substrate were effected along two parallel linear transects lying between the outer reef and the lagoonal reef. Ground truth observations were also effected on and around lagoonal coral patches. The observations consisted of video and 35mm camera shots, together with manual visual annotations.

Data Analysis: On account of the relatively high correlation of the XS1 and XS2 channels for the area of interest (cross-correlation coefficient $r_{xs1,\,xs2} = 0.51$ for a total of 31,200 pixels), analysis by principal components results in the first principal component accounting for 86.1% of the total variance, which is not favourable to good thematic classification. A bidimensional histogram of the XS1 and XS2 channels is presented in Figure 2. The boomerang-like shape of the histogram distribution is noticeable, indicating that it might be more useful to represent the bidimensional histogram in polar coordinates. Therefore, to reduce the amount of correlation between the two channels and improve the discrimination of the main reef themes, a non-linear polar coordinate transformation is applied to XS1 and XS2, creating two pseudo-bands, the radial distance ρ^* and the angle θ^*:

$$\rho^* = \mathrm{hypot}(XS1, XS2)$$
$$\theta^* = \mathrm{atan}^{-1}(XS2/XS1)$$

where, the function "hypot" is defined as:

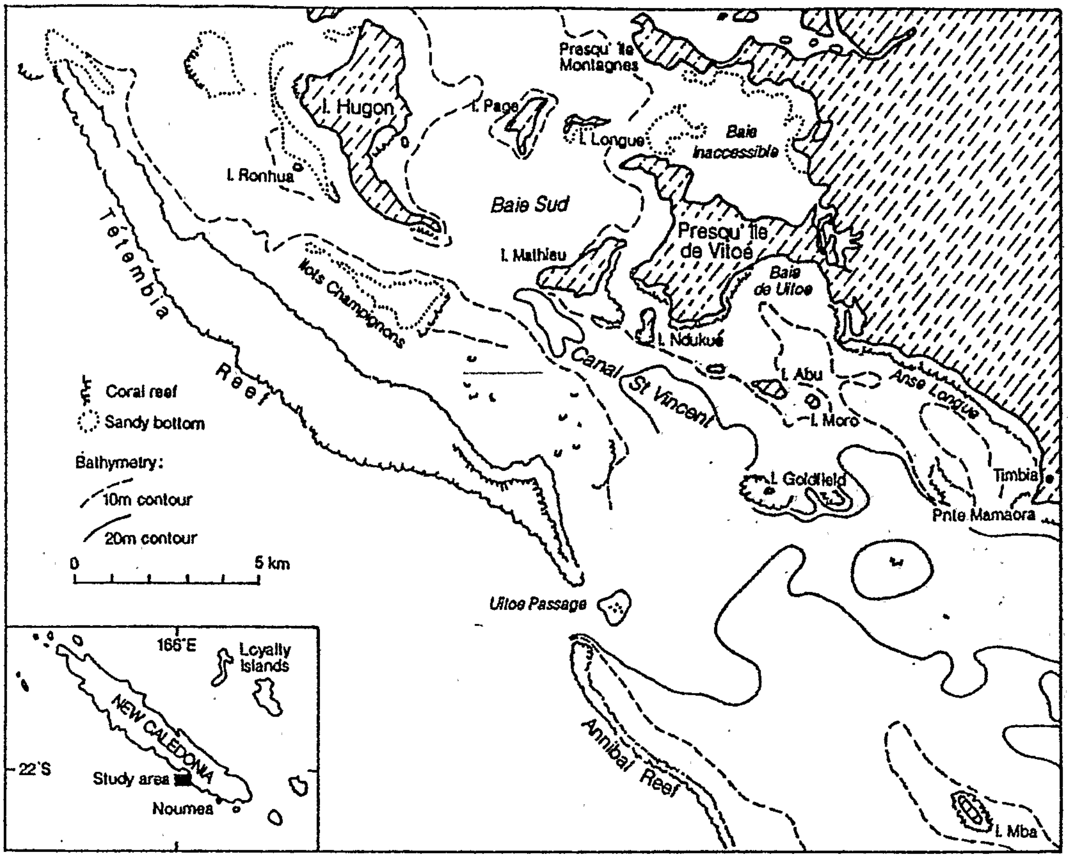

Figure 1. Location map, showing the Tétembia Reef and area of interest.

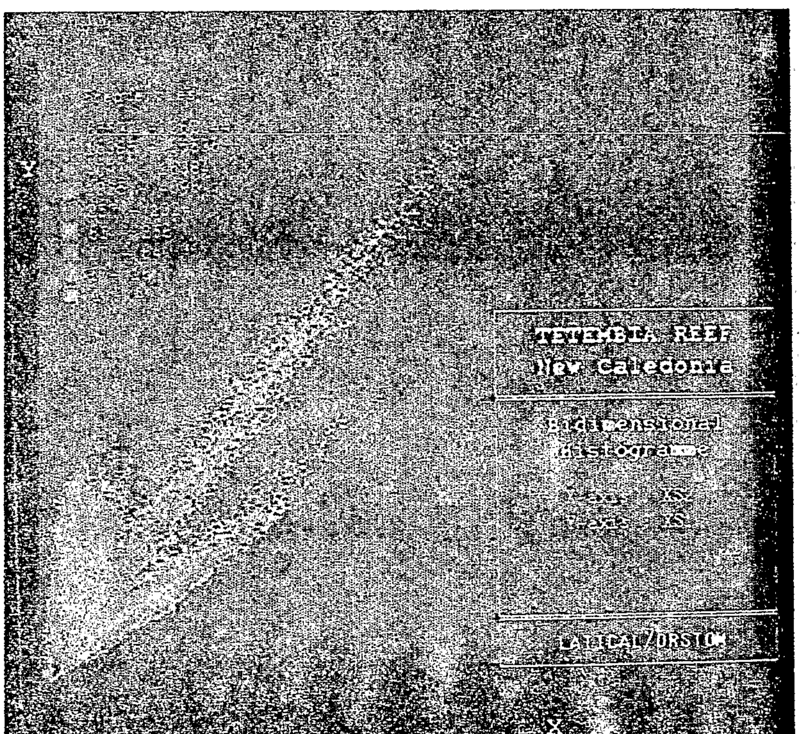

Figure 2. Tétembia reef, XS1-XS2 bidimensional histogram.

$$\text{hypot} = ((XS1)^2 + (XS2)^2)^{\frac{1}{2}}$$

The cross-correlation coefficient $r_{\rho,\ \theta}$ for the same area of interest has been reduced to -0.33, with the first principal component now accounting for 79.4% of the total variance. The optimal polar coordinate transformation which provides the maximum discrimination of the coral reef themes has been found to be given by:

$$\rho = ((XS1)^2 + (XS2)^2)^{\frac{1}{2}}$$
$$\theta = \text{atan}^{-1}((XS2 - 10)/(XS1 - 22))^{0.75}$$

The resulting bidimensional histogram is shown in Figure 3.

To separate submerged coral substrate types which have very similar spectral variations and enhance local structural heterogeneities, a texture pseudo-channel was created. The texture channel, τ, is the computed local standard deviation between a central pixel value in a given 3 x 3 mask and its neighbouring eight pixel values (Jupp *et al.*, 1985). That is, for a given pixel p_{ij} in scan line i and column j;

$$\tau_{ij} = \frac{1}{8}\left(\sum_{n,m}^{8} |p_{ij} - p_{nm}|^2\right)^{\frac{1}{2}}$$

where the sum is taken over all (n, m) in a clique centered at p_{ij} such that only near-neighbour interactions are considered, that is;

$$\max\{|i-n|, |j-m|\} = 1 \qquad \forall n, m = 1, 2, \ldots 8$$

Texture pseudo-channels were evaluated for two types of "pigmentation indices":

$$\tau^{(1)} = \text{local s.d. of } \left(\frac{XS1}{XS2}\right),$$

and

$$\tau^{(2)} = \text{local s.d. of } \left(\frac{(XS1)^2}{XS2}\right).$$

Figure 4 shows a false colour composite image of the eigen-bands as a result of principal component analysis on ρ, θ and $\tau^{(2)}$. No significant differences were found between images with the two pigmentation indices $\tau^{(1)}$ and $\tau^{(2)}$, with the exception that the $\tau^{(2)}$ channel provided an increased level of detail around areas of heterogeneities, such as those found around coral patches and in the furrows between the lagoonal reef and lagoon flat.

A thematic map is obtained by aggregating the spectral classes into major groups or clusters which match, as near as possible, the reef substrate that they map. The aggregation or classification process is supervised whereby a training set of spectrally homogeneous pixels identifiable on the image is used to "seed" the classifier. Coral reef theme mapping was undertaken by implementing a variety of supervised classification methods. These included the parallelepiped, Euclidean distance, and maximum likelihood estimation (MLE) parametric classifiers. Prior to using these classifiers an interactive "inverse mapping" method is employed whereby a training set obtained during ground truth measurements of the coral substrate is located on the image and mapped into the ρ-θ bidimensional histogram. Each pixel which has a similar radiance value in both channels will be mapped into a unique cluster in the histogram space. All pixels belonging to the space spanned by each cluster in the bidimensional histogram space are then mapped back into the original image, thereby obtaining a raw thematic map. This process is repeated iteratively until all pixels in the training set are satisfied and disjoint clusters are produced. Any remaining unclassified pixels are then classified by applying parallelepiped or MLE supervised classifiers.

Results and Discussion

Structural Analysis of the Reef: The combination of the three pseudo-channels θ, ρ and $\tau^{(2)}$ (or alternatively $\tau^{(1)}$) has provided information relevant to shallow reef substrate structures, particularly with reference to;

- the morphology of the slope and spur-and-groove zone of the lagoonal reef, and
- the outer reef flat surge channels and grooves.

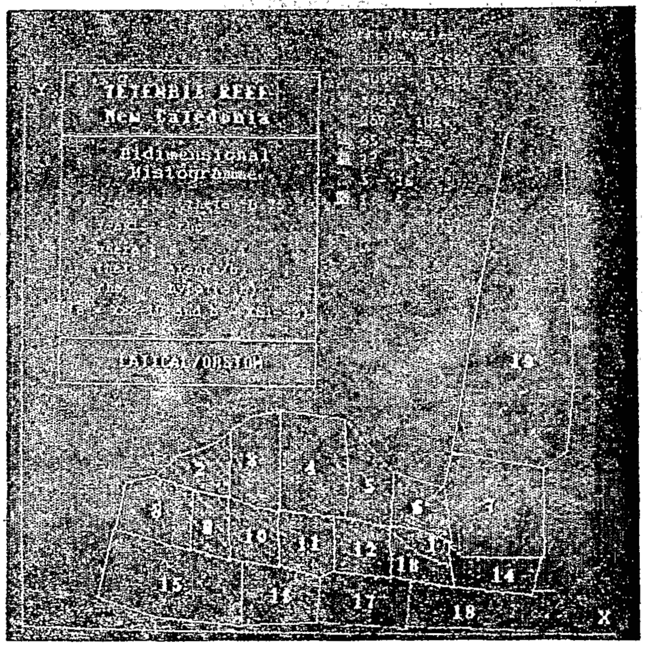

Figure 3. Tétembia reef, ρ-θ bidimensional histogram (Spectral class labels have been included, see text)

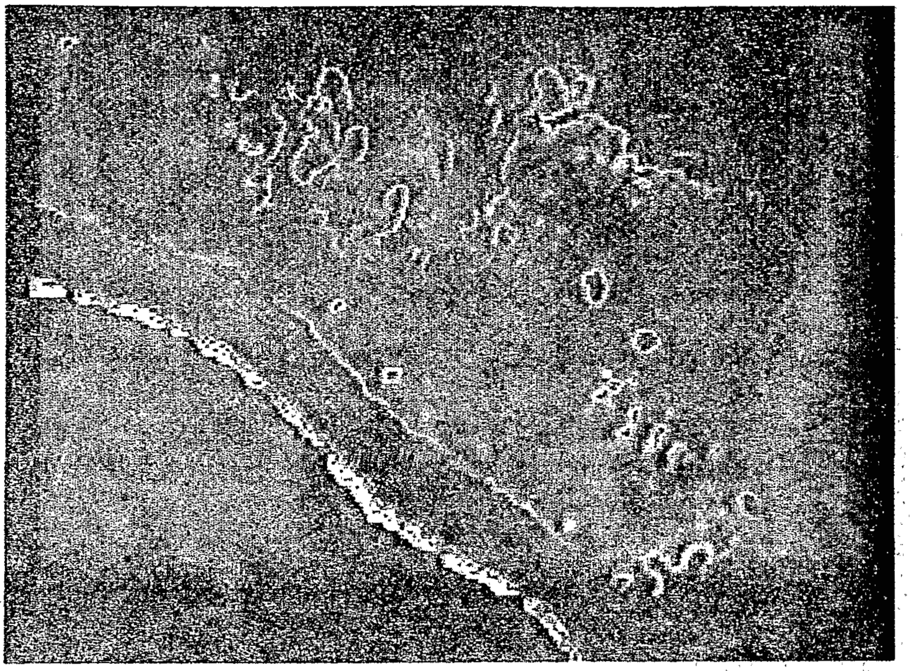

Figure 4. Colour composite of θ, ρ and $\tau^{(2)}$, after principal component analysis.

It has also enhanced details pertaining to the zones of intermediate bathymetry, such as;

- heterogeneities in the lagoon bottom due to tidal channels, and
- the delineation of the perimeter of lagoonal coral patches.

Spectral Classification and Thematic Mapping: A thematic map of the Tétembia reef was obtained by effecting a pre-classification using the inverse mapping spectral classification method and then followed by a MLE classification. Figure 5 shows the results of this classification procedure. More detailed subscenes of this thematic map are shown in Figures 6 and 7. Figure 6 provides details relating to the inner reticulate reef and lagoonal coral patches. Figure 7 shows the themes on the outer reef platform and lagoonal soft bottom interface. The classes and corresponding class numbers are overlayed on the ρ-θ bidimensional histogram (Figure 3). The description of the various themes is given by the spectral classification model (Table 1).

The classes generated by this classification procedure are located in the ρ-θ bidimensional histogram in an approximately regular matrix pattern, where the vertical ρ-axis corresponds to a measure of bathymetry (small values of p equivalent to deeper water) and the horizontal θ-axis providing qualitative information on the gradient in the coral-to-sand areal density ratio, and on the areal density of living coral (at constant bathymetry).

Ground truth verification of the map led to the following observations and conclusions relevant to both general coral reef themes and hard substrate themes.

General Coral Reef Themes: The following general coral and soft bottom themes have been identified:

- The morphology of hard substrate covers in shallow water is similar on the outer reef platform and on the reticulate lagoonal reef (themes 1, 5, 6 and 13). This is characterised by massive slabs covered with rubble and scattered with *Favidae* and *Porites* corals. French National Geographic Institute (IGN) aerial photographs, together with ground truth observa-

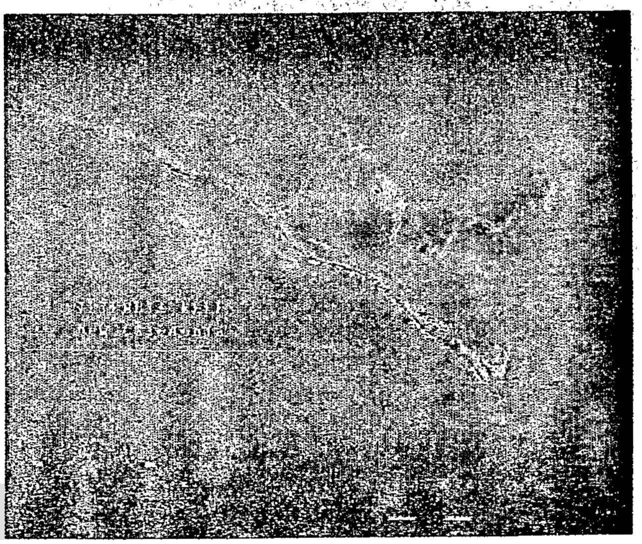

Figure 5. Thematic map of Tétembia reef (See Table 1 for theme definitions).

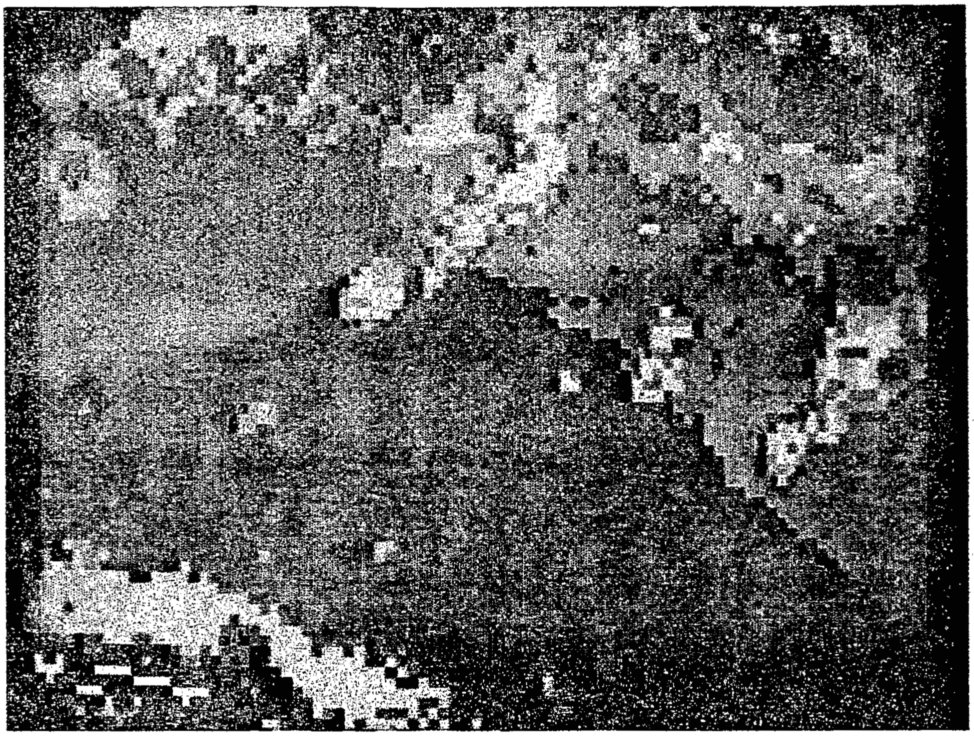

Figure 6. Thematic map of Tétembia reef showing details of inner reef and coral patches.

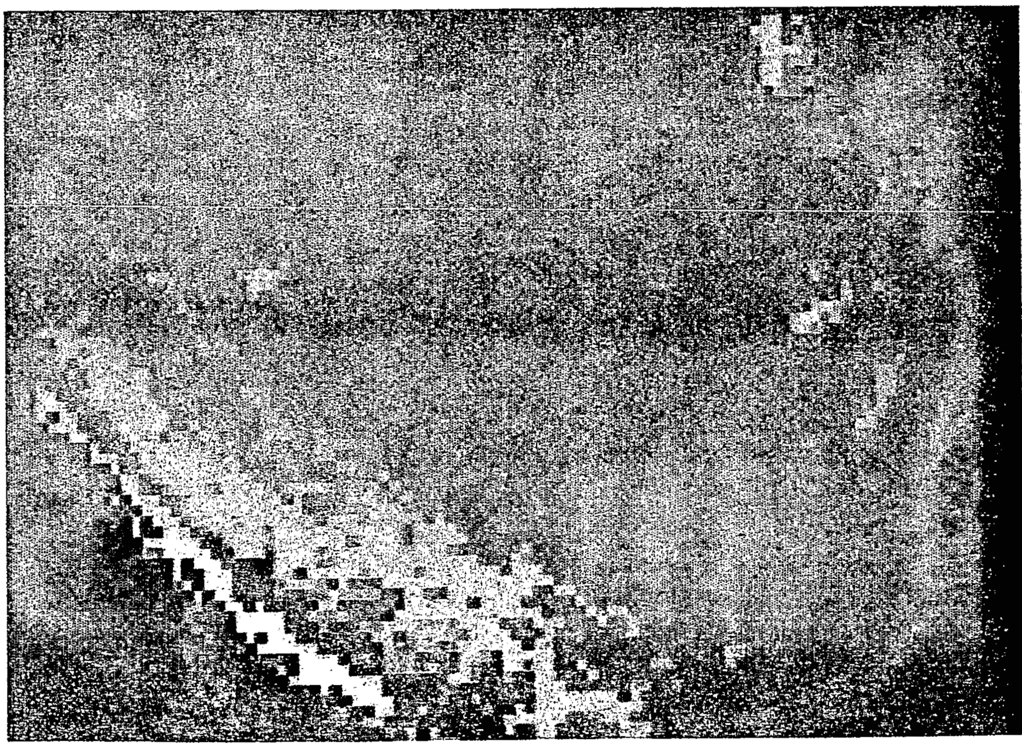

Figure 7. Thematic map of Tétembia reef showing details of outer reef platform.

Class Label	Class Number	General Class Description
Shallow sand	2	Shallow lagoonal sandy bottom
Deep sand	8	Deep lagoonal sandy bottom
Coral débris	9 and 10	Lagoonal coral débris
Shallow coral I and II	5 and 6	Surface reef platform coral (*Favidae*)
Shallow coral III and IV	1 and 13	Reef platform coral (*Acropora* channels)
Deep coral I and II	11 and 12	Reef platform slope (2 - 5m, *Acropora*)
Sand/coral	3 and 4	Sandy bottom coral interface
Reef platform	7 and 14	Outer reef platform and surface débris
Shallow water	15 and 16	Inner lagoon shallow water (5 - 10m)
Deep water	17 and 18	Inner lagoon deep water (> 10m)
Reef margin	19	Outer reef margin and exposed reef

Table 1. Spectal classification model for Tétembia reef.

tions, show that some of these slabs have tidal surge channels which are aligned along the radius of curvature of the outer reef and are filled with branching corals (*Acropora*).

- Living corals have been identified on the reef slabs (themes 1, 5, 6 and 13) as well as on the inner slope of the outer reef, on the base of certain sections of the reticulate lagoonal reef, and around the perimeter of coral patches (themes 11 and 12). These living corals are principally of the *Favidae* and *Porites* varieties for shallow water depths, and of the branching *Acropora* type in deeper water. The two types of coral do not appear to be differentiated by depth but rather by their densities. A gradient in the living coral-to-dead coral areal density ratio along the θ-axis has also been observed (themes 8 to 13 inclusive and theme 1 correspond to an increasing gradient in the living coral-to-dead coral areal density ratio). A detailed analysis of the distribution of coral types indicates that living corals congregate around the North-West side of the coral patches and inner lagoonal reef, protected from the predominant South-East trade winds.
- Coral débris (themes 9 and 10) has been correctly identified around the base of sections of the inner slope of the outer reef, around the perimeter of the coral patches, and on the northern side of the reticulate reef. It is thought that the density and distribution of coral débris is significantly affected by the passage of cyclones.
- The soft bottom covers have been separated into two themes (2 and 8), both having the same covers consisting of white sands with scattered patches of branching corals (the area covered by the latter being less than the resolution of the image). Theme 2 corresponds to a shallow (0 - 5m approx.) sandy bottom, whereas theme 8 is identified with a deeper sandy bottom (> 10m).

Hard Substrate Themes: The hard substrate themes have been divided into three categories:

- The outer reef platform and the reticulate lagoonal reef consist of submerged slabs at shallow depth and with small slopes covered with dead coral interspersed with living *Favidae* and *Porites* corals (themes 5 and 6). These living corals are also present, at lower densities, on the platforms of submerged (< 2m) lagoonal coral patches.
- The inner slope of the outer reef and along the base of the southern section of the reticulate lagoonal reef are characterised by dense populations (themes 11 and 12) of living *Acropora* branching corals and *Tubinaria* corals in deeper water (> 2m). Branching corals have also been identified in the shallow waters of the tidal surge channels of the outer reef platform and over scattered areas of the reticulated reef platform (themes 1 and 13).
- A sand/coral interface corresponding to the transition between the soft bottom and living branching coral has been identified (themes 3 and 4).

Conclusions

The thematic mapping of shallow coral reefs using high-resolution SPOT has identified various substrate themes. Such themes include soft bottom themes, coral débris, and living corals. By selecting an appropriate transformation of the XS1 and XS2 channels, the ρ-θ transformation, the identification of these themes has been made possible. A gradient in the living coral-to-dead coral areal density ratio along the θ-axis has also been observed. It is hoped that a quantitative evaluation of this gradient can be obtained.

Current research involves extending the spectral transformation and classification methods to other areas of the New Caledonia reef. It is also hoped that, through the repetitivity of scenes, the monitoring the temporal changes, such as those due to the passage of cyclones, can be made possible.

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